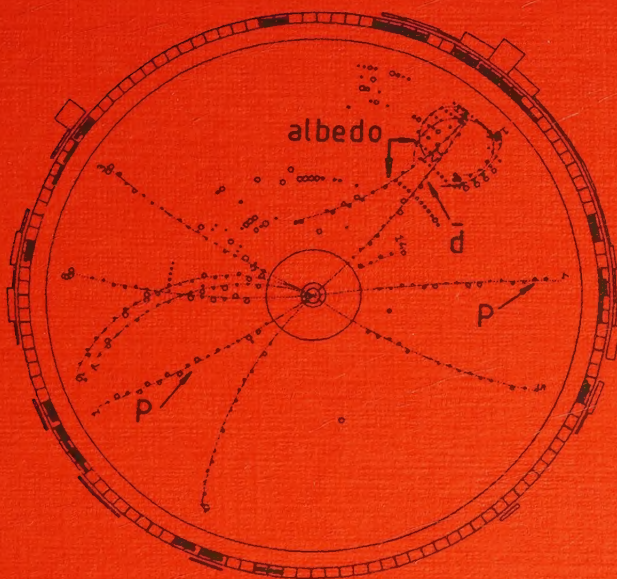


A STUDY OF PARTICLES PRODUCED IN e^+e^- ANNIHILATION AT A CENTER-OF-MASS ENERGY OF AROUND 10 GeV, USING IONIZATION LOSS MEASUREMENTS.

Yukio Oku



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ARGUS MAGNETIC FIELD MEASUREMENTS

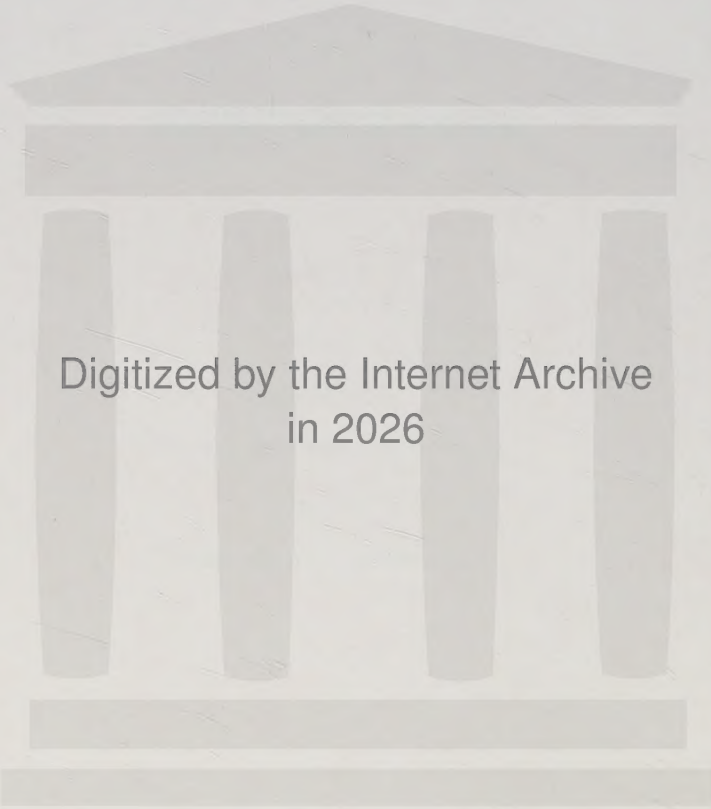
by

R.L. Childers

University of South Carolina, USA

Y. Oku

University of Lund, Sweden



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ABSTRACT

This report describes the measurement and parametrization of the ARGUS magnetic field. The field calculated from the parameters reproduces the measured field to within a few parts per thousand.

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- I. Introduction
- II. Apparatus, Calibration and Measurements
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I. Introduction

The magnetic field intensity in the interior of the ARGUS detector was measured between 27 March and 2 April, 1982. The volume in which most of the measurements were made was essentially that to be occupied by the drift chamber (figure 1). The BEBC-field mapping system from CERN was used to make and record the measurements.

Measurements were made of the field components B_z , B_ρ and to a lesser extent, B_ϕ , for three different configurations of the inner compensation coils. Figure 2 shows the coordinate system used. The compensation coil configurations, or connection schemes, are designated 100%, 50%, and 0% compensation and are shown in Figure 3. The discovery of a high-resistance short-to-ground in coil number four on the $+z$ side dictated the use of the coil configurations shown because it was not possible to repair the coil in less than several months. The measurements made and the spacing between the measured points was to some extent dictated by the time available.

The data were recorded on duplicate floppy discs from which IBM tapes were later prepared at CERN and sent to DESY. The B_z and B_ρ components have been parameterized and an analytic expression found for the B_ϕ component.

Prior to the main field measurements a series of measurements was made to determine the effect of the magnet's immediate history on the field. The stray field also was measured at a number of places outside the main magnet coil. Other runs were made to check the reproducibility of the probes and the reproducibility of the mechanical positioning mechanism. All measurements, with the exception of the magnetization measurements, were made at 95% of the maximum rated current of the power supply (4275 amps). With the current flowing in the normal direction the solenoid corresponds to a bar magnet with its north pole at the east ($+z$) end of the ARGUS detector. (B_z is negative).

II. Apparatus, Calibration and Measurement

When the magnet is energized the only access to the field region is through the central axis of the mini-beta quadrupoles. (Fig. 1). The mechanical positioning of the probes, as well as the feed-through for the cables, had to be made through these holes. A sketch of the mechanical framework for holding and moving the probes is shown in Fig. 4. The supports I, II and III on which the hall probes were mounted were fixed with respect to one another and could be moved along the z axis as a unit by means of the hollow tube T. The cables for the 185 hall probes passed through this tube. The tube T was attached to a carriage which could be remotely positioned with a precision of 0.2 mm along the z axis. The spacing between the measuring points was 50 mm in the z and ρ direction and 30° in ϕ (Figure 5).

The measuring procedure was to start with the apparatus at some fixed angle and at the east end of the magnet. All of the probes were then read out. The carriage was then advanced 50 mm and the probes read out again. This continued automatically until the western limit had been reached. Then the apparatus was returned to the eastern end and rotated to a new angle and the procedure repeated. As a check one complete traverse along the z axis was repeated. In addition to the hall voltages, the temperature in the magnet, the magnet current and the time were recorded on the floppy disks.

The probes in their mounts were calibrated at CERN against an NMR probe using a magnet of uniform field. They were calibrated as a function of temperature and of magnetic field. A separate calibration curve was established for each probe. When the differences between the NMR values and those determined from the calibration constants is plotted, the width at half-maximum of the distribution is approximately 5 Gauss.

III. Magnetization

A series of measurements was made to detect the effect of the magnetic history of the iron yoke on the magnetic field for a given excitation current. This was done by varying the current while keeping the probes fixed at one position. The readings of one probe as a function of current are shown in Fig. 6. To a good approximation there was no observed effect due to the history, and the data fit a straight line with a r.m.s. deviation of 7 Gauss.

During these measurements it was found that the power supplies could not continuously deliver the maximum rated current. For this reason it was decided to make all readings at 4275 A, which is 95% of the maximum rated current. This is the current used during data taking.

IV. Stray Fields

The stray fields outside the coil were measured at some of the photomultiplier tube housing positions. After the main magnetic field measurements were made, the current was set to zero and the stray fields measured. The zero current fields were nowhere greater than five Gauss, typical values being less than two Gauss. With the magnet and compensation coils excited, typical values for B_z were less than 35 Gauss, those for B_ρ less than 15 Gauss. With the exception of the regions near the current connections for the main coil the field was nowhere greater than 70 Gauss.

V. Symmetry

Two types of geometrical symmetry were checked for : symmetry in ϕ and symmetry in z . Only the B_z component was considered because the B_ρ data required too many corrections to be usefully employed for this purpose.

If the field is symmetric in ϕ a given probe should read the same at all angles. A histogram of the difference between the average for all angles and the value at one angle reflects any deviation from symmetry. If there is no asymmetry the histogram will reflect the reproducibility of the probes and precision of mechanical alignment. The first two columns in Table 1 show the r.m.s. values of this distribution for each compensation, first in percent and then in Gauss.

A similar test was made of the symmetry about the midplane ($z=0$) by subtracting the readings at each value of $+z$ from the value at the corresponding point at $-z$. The r.m.s. values of this distribution are shown in the third and fourth columns of Table 1.

To determine the relative importance of the asymmetries, they have been compared with an estimate of the measurement uncertainty. Due to the overlap region between the supports it is possible to read the field at the same point in space with two different probes. The r.m.s. average of the differences between two probes reading the same point has been taken as an estimate of the measurement error. This way of estimating the measurement error will include the effects of probe misalignment. These are listed in columns five and six of Table 1. The increase in measurement error with greater compensation reflects the fact that precision in position is more important in non-uniform fields. That the errors are larger for the radial component than for the axial component is expected from the discussion later in Axial and Radial Components.

A comparison of the values in Table 1 lead to the conclusion that the field is symmetric within the measurement errors, both in ϕ and about the plane $z = 0$.

VI: The Tangential Component (B_{ϕ})

One does not expect a ϕ component for the magnetic field of a perfect

solenoid. A number of things can give rise to such a component for real solenoids; for instance, the coil may not be perfectly circular, or there are unaccounted-for currents. There is not, however, a contribution inside the coil due to the longitudinal component of the current in the coil. This gives rise to a field outside the coil which is the same as that due to a straight wire on the axis and carrying the same current as the coil. In order to detect any ϕ component seven probes were placed so as to measure B_ϕ . They were placed at the ends of the long arms on supports I and III. (See Fig. 4). The observed field readings were not zero and ranged from -100 Gauss to +200 Gauss.

The observed values of B_ϕ seem to be satisfactorily explained by the sum of several terms;

B_α : When a probe is not perfectly aligned it will detect less of the component for which it is intended and will detect some part of the other components. Since B_z is large, the misalignment of a probe by only 5 milliradians can change the probe's reading by 35 Gauss. B_α is a term due to the gross misalignment of a probe with respect to the coordinate system of the measuring machine.

B_{k_1} : If the axis of rotation of the measuring machine is not parallel to the symmetry axis of the field, there will be a change in the B_ϕ projection of the B_z component as the machine is rotated about its axis. This can not easily be shown in a static drawing, but can easily be seen by making a simple cardboard model and rotating it. This term can be approximated by $k_1 (90 - \phi)$ if the machine axis is in the y-z plane but not parallel to the z axis. The constant k_1 should be the same for all probes.

B_{k_2} : If there is some rocking of the axis as the machine is rotated, due, for instance, to imperfections in the bearing rings at the end, another variation is introduced. If the motion of this axis is entirely in the x-y plane, the contribution to the probe reading can be approximated by $k_2 |90 - \phi|$ where $0 < \phi < 180$. The restriction on the angle corresponds to the

way in which measurements were actually made. The constant k_2 should also be the same for all probes.

B_{wire} : The coils are separated by a spacing of 5 cm. (See Figure 1), and are connected to the adjacent coil at the same angular position by conductors which are 165 cm from the z-axis. If one assumes that far from the connector they can be treated as a long straight wire, and if one takes into account the orientation of the hall probes and the direction of the magnetic field, then an analytic expression for this term can be written.

If the above four terms are the only ones, then one can write

$$B_{\alpha} \text{ (observed)} = B_{\alpha} + k_1 (90 - \phi) + k_2 |(90 - \phi')| + 885 \frac{\rho - 165 \cos(180 - \phi)}{\rho^2 + (165)^2 - 330 \cos(180 - \phi)} \quad (1)$$

where ρ is the distance from the z axis to the probe in question. The geometry of the placement of the probes on the different supports requires that for support III $\phi' = \phi$ and for support I $\phi' = \phi - 180$. The same considerations require $k_2' = k_2$ for support III and $k_2' = -k_2$ for support I.

B_{α} is different for each of the seven probes but may easily be determined from the $\phi = 90^\circ$ reading. The constants k_1 and k_2 should be approximately the same for each probe if the above argument is correct in its essentials. The reading of each probe as a function of ϕ was fit by a least-squares technique to the above equation. The parameters were found to be quite closely grouped. When all the probes are fit at once with the above two-parameter equation, B_{α} having been determined from the previous fit, the parameters are $k_1 = -0.11$ and $k_2 = 0.04$. The residuals between the prediction of the equation with the above parameters and the measured values are shown in Figure 7. The r.m.s. value of the distribution is 1.4 Gauss.

The closeness of the fit strongly suggests that the only real B_ϕ component is that due to the connectors between the coils. This does not need to be parametrized and in the volume occupied by the drift chamber is given by the expression for the field due to a long wire carrying 4275 A located 165 cm from the z axis at $\phi = 180^\circ$.

Credence is given to this view by looking at a plot of B_ϕ vs. z for several probes in Figure 8. Note that the period of the fluctuation of the probes corresponds to the coil-to-coil spacing and that as one goes away from the coil connectors the curve becomes smoother.

VII. Axial and Radial Components; B_z and B_ρ

For each of the three compensation coil configurations the components B_z and B_ρ were each measured at 7224 points (43 points along the z-axis x 14 radial positions x 12 angles, see Fig. 5). The space between the measuring points in the z- ρ plane was 5 cm and readings were taken every 30° . The innermost probe was 20 cm from the z axis and the outermost was 85 cm.

The two principle sources of error for most of the measuring volume were probe calibration error and probe alignment error. The calibration errors are within allowable limits but the geometrical alignment and positioning errors were corrected for in some cases.

If a probe is intended to read a field B_n , to which it is nominally perpendicular, but is in fact misaligned by some small angle α , the reading will be

$$B_{\text{obs}} = \cos \alpha B_n + \sin \alpha B_p \quad (2)$$

when B_p is the field component perpendicular to the intended field component.

For the B_z component $B_n \approx 8,000$ Gauss and B_p (the ρ component) is of the order of 400 Gauss at most. This means that an 8,000 Gauss field would, for a misalignment of .0175 radians (1°) be read as 2 Gauss

less than 8000 Gauss, or 1 part in 10^{+3} too small. Since the construction of the apparatus gives the best angular positioning to the probes which measure B_z (estimated to be ± 5 mrad) the B_z readings have been taken without any corrections. The differences between the probe readings in the overlap region is typically less than $1/10^3$ and no adjustment has been made. Figures 9, 10 and 11 display the measured B_z field without any corrections. The field is essentially the same at all angular slices through the chamber volume. (See section V, on symmetry).

When the raw B_ρ data were plotted they were found to be quite unsymmetric about the $z = 0$ plane. This would not be expected to be the case because a relatively high degree of symmetry was observed in the z component. If the field is exactly symmetric about the mid plane and has no ϕ component, then $B_\rho = 0$ at $z = 0$. However, this lack of observed symmetry is easily understood because the roles of the components are interchanged in Equation 2. If a probe is slightly misaligned by some angle α , each reading will have an additional component of $\sin\alpha \cdot B_z$, which will be 40 Gauss for a 5-mrad misalignment in an 8000 Gauss B_z field. To correct for this, an amount $\Delta_1 B_\rho$ was added to, or subtracted from the reading of each B_ρ probe on support II to make it read zero at the $z = 0$ plane. Using the measured value of B_z for the same location, an angular misalignment was found for each probe on support II ($\sin\alpha = (\Delta_1 B_\rho) / (B_z(z=0))$). The readings of each probe on support II were then corrected for each position of z by adding (or subtracting) the quantity $\sin\alpha B_z(z, \rho)$. This process was continued at the overlap regions, finding an angular misalignment for the probes on plates I and II and correcting their readings by $\sin\alpha \cdot B_z(z, \rho)$, where again $B_z(z, \rho)$ is the measured value of B_z at that point. Figures 12, 13 and 14 show the shape of the B_ρ component of the fields, corrected as indicated above. Note that although the field is relatively uniform over most of its volume, it is increasingly inhomogeneous near the compensation coils as the percentage compensation increases.

VIII. Parametrization

It is useful to employ a coordinate system which displays the same symmetry as the field being parametrized. In the case of cylindrical symmetry the most obvious choice is to make an expansion in terms of Bessel functions^{1,2,3}. For calculational simplicity in our case we have chosen rather an expansion in terms of Legendre polynomials which is also a solution to Laplace's equation⁴. In the case of rotational symmetry ($B_\phi = 0$), the general expression reduces to

$$B_z = \sum_{l=0}^{\infty} (1+l) a_{l+1} r^l P_l(\cos\theta) \quad (3)$$

and

$$B_\rho = \sum_{l=0}^{\infty} a_{l+1} r^l \sin\theta \frac{d}{d\cos\theta} P_l(\cos\theta) \quad (4)$$

where r is the distance between the point and the origin and θ is the angle between r and the z -axis. The same parameters, a_i , enter into the expressions for B_z and B_ρ because the formulas are derived from a single scalar potential.

The parametrization of the field will be discussed separately for each compensation because the procedures were slightly different for each case. This was because of the increasing inhomogeneity which can be seen in Figures 9 through 14.

For the most uniform field (0% compensation), a simultaneous fit was made over the entire measured volume to both B_z and B_ρ values by minimizing the expression

$$\chi^2 = \frac{\sum_z (B(\text{meas}) - B(\text{calc}))^2}{\sigma_z^2} + \frac{\sum_\rho (B(\text{meas}) - B(\text{calc}))^2}{\sigma_\rho^2} \quad (5)$$

This two-dimensional fit takes advantage of all the data and gives a result which is consistent with Maxwell's equations.

Several criteria were used to determine the most suitable number of

parameters. As an upper limit the number of parameters should be less than two times the square root of the number of data points to avoid the Runge phenomena. However the r.m.s. difference between the measured values and the calculated values should be less than the measurement uncertainties. Lastly there is little reason to increase the number of parameters beyond the point that the ratio of χ^2 to the number of degrees of freedom becomes constant.

Using this procedure it was possible to obtain a reasonable fit with ten parameters. A fit with χ^2/DF much smaller than normally required was also made. This latter fit was used for the second parametrization discussed in the next paragraph in order to minimize the effect of making a least-squares fit to a least-squares fit. The r.m.s. residuals between the field calculated using a thirty-one parameter fit ($\chi^2/DF = 0.098$) and the measured field are given in table 2. A program which gives both field components as a function of position is available. Though the result is satisfactory, the relatively large number of parameters and the time required for evaluating the Legendre polynomial series make this procedure unsatisfactory for use in a track reconstruction program. A technique which is sometimes used to overcome this difficulty is to construct an adequate grid of field values which are stored as a look-up table.

A different approach was used by changing to a one-dimensional fit to a polynomial in z for each of the thirty-six layers in the ARGUS drift chambers. This second parametrization gave a different set of parameters for each layer, but only six or seven parameters at most for each layer. This reduces the computational time to an acceptable level. This second fit was made to the field calculated from the Legendre polynomial series for two reasons: the first parametrization took advantage of Maxwell's equation and, to some extent, corrected the data; furthermore these results can be extended into regions where measurements were not possible, such as the vertex region.

This procedure will obviously give discontinuities between layers, but in practice this has turned out to be acceptable. The results of

this fitting procedure and the discontinuity checks are given in Table 2.

For the case of fifty percent compensation the increased inhomogeneity of the field made it desirable to break the field into several regions for the fit to the Legendre polynomial series. Again the fit was made to the B_z and B_ρ data simultaneously. A second parametrization was made as before, resulting in about five parameters for each drift chamber layer and the residuals as shown in Table 2. For the fifty percent case in regions of high field gradient near the compensation coils, a set of cubic spline functions have been provided.

For the most inhomogeneous case, (100% compensation) the Legendre fit was made in one dimension layer by layer, rather than in two dimensions. The polynomial fit was then made exactly as in the case of fifty percent compensation. Again the number of parameters was approximately five for each layer. The results are shown in Table 2. In all of the fitting procedures for each compensation the ratio of χ^2 to the number of degrees of freedom has been much less than unity.

IX. Other Regions

In the vertex region no measurements were taken except on the z axis itself. An extrapolation of the Legendre fit to the z axis gives good agreement as shown in Table 3. A second parametrization was done in layers separated by one cm. The r.m.s residuals between the Legendre fit and the polynomial fit were between two and five Gauss for all.

In the shower counter region the field was determined using the NUTCRACKER field calculation program from SLAC. The precision is estimated to be approximately 1% in this region.

Inside the compensation coils the results of the NUTCRACKER program were used to establish a grid of field values which was stored and

interpolated in two dimensions.

In the case of the shower counter and compensation coil regions the absolute value of the results of the NUTCRACKER program were not used. The results of the program were adjusted so as to match the parametrized field at the boundaries of these regions.

Acknowledgements

We would like to thank F. Wittgenstein and the members of the BEBC field mapping system group from CERN for their help in the design and carrying out of the measurements. We gratefully acknowledge the help of H. Albrecht, M. Boileau, H. Schröder and F. Wittgenstein for their part in making the measurements. For suggestions concerning the parametrization we are indebted to H. Albrecht, P. Böckmann, D. Coppage, H. Gennow, P.M. Patel, A. Philipp and H. Schröder. We thank the DESY directorate for their hospitality and support. We want to particularly thank W. Schmidt-Parzefall for his support and encouragement. This work was supported in part by the U.S. Department of Energy Contract DE-A509-80ER 10690 and by the Department of Elementary Particle Physics, Institute of Physics, University of Lund, Sweden.

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Table 1

Tests of Symmetry

Compensation percent	Φ Symmetry Test		Reflection in mid plane (z=0)		Measurement uncertainty	
	I	II	III	IV	V	VI
	$\frac{B - \langle B \rangle}{-z} \times 100$ $\frac{\langle B \rangle}{z}$ percent	$B - \langle B \rangle$ $\frac{z}{z \text{ rms}}$ Gauss	$\frac{B (+z) - B (-z)}{\langle B (-z) \rangle}$ percent	$B (+z) - B (-z)$ $\frac{z}{z}$ Gauss	σ_z Gauss	σ_p Gauss
0	0.063	4.3	0.063	7.4	14	35
50	0.067	4.6	0.067	9.5	18	44
100	0.075	5.3	0.078	9.5	19	49

Table 2
Results of Least-Squares Fitting Procedures

Compensation percent	Using Legendre Polynomials		Using Polynomials in z		
	$\langle B(\text{fit}) - B(\text{data}) \rangle_{\text{rms}}$ (Gauss)		$\langle B(\text{Legendre}) - B(\text{po}) \rangle_{\text{rms}}$	$\langle B(\text{po}) - B(\text{data}) \rangle_{\text{rms}}$	Discontinuity $\langle B(\text{layer}) - B(\text{layer}+1) \rangle_{\text{rms}}$
0	B	4.9	2.8	6.6	10
	z				
50	B	9.8	3.0	11	7
	ρ				
100	B	13 in sensitive d.c. area	4	21	16
	z	56 outside			
50	B	15 in sensitive d.c. area	5	22	4
	ρ	85 outside			
100	B	7	3	9	9
	z				
100	B	15	5	16	9
	ρ				

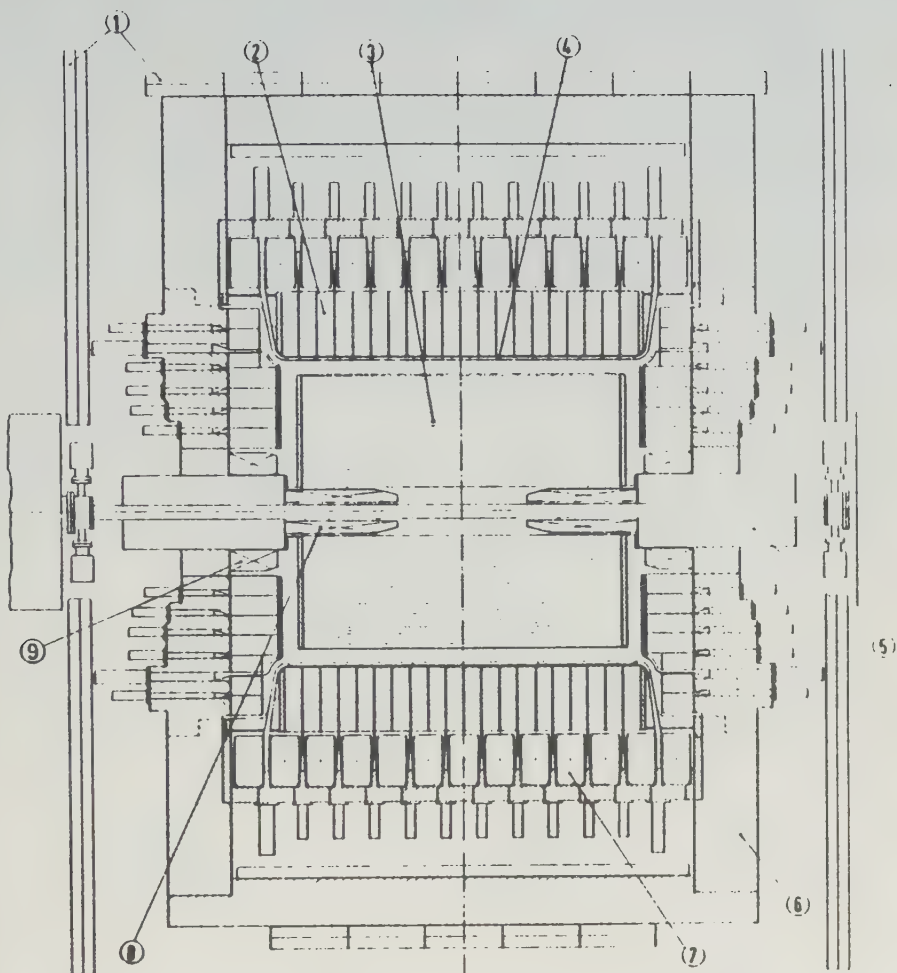
Table 3

Extrapolation of Legendre fit to $z=0$, $p=0$

Compensation	Data (Gauss)	Extrapolation (Gauss)	Difference (Gauss)
0 %	- 7577	- 7577	0
50 %	- 7514	- 7520	6
100 %	- 7449	- 7456	7

FIGURE CAPTIONS

- Fig. 1. The ARGUS Detector
- Fig. 2. ARGUS Coordinate System
- Fig. 3. Compensation Coil Connections
- Fig. 4. Mechanical Mounting of Probes
a) Overall view, b) schematic drawing of probe support arms, c) end view of one support
- Fig. 5. Measuring Grid
- Fig. 6. Magnetization Measurement
- Fig. 7. Residuals between B (measured) and B (calculated)
- Fig. 8. B as a function of ϕ
- Fig. 9. Measured B_{ρ} field at 0% compensation
- Fig. 10. Measured B_z field at 50% compensation
- Fig. 11. Measured B_z field at 100% compensation
- Fig. 12. Measured B_z field at 0% compensation. Corrected for probe misalignment
- Fig. 13. Measured B_{ρ} field at 50% compensation. Corrected for probe misalignment
- Fig. 14. Measured B_{ρ} field at 100% compensation. Corrected for probe misalignment



1. Muon chambers
2. Shower counters
3. Drift chamber
4. Time of flight counters
5. Mini beta quadrupole
6. Iron yoke
7. Solenoid coils
8. Compensation coils (inner)
9. Compensation coils (outer)

Fig. 1

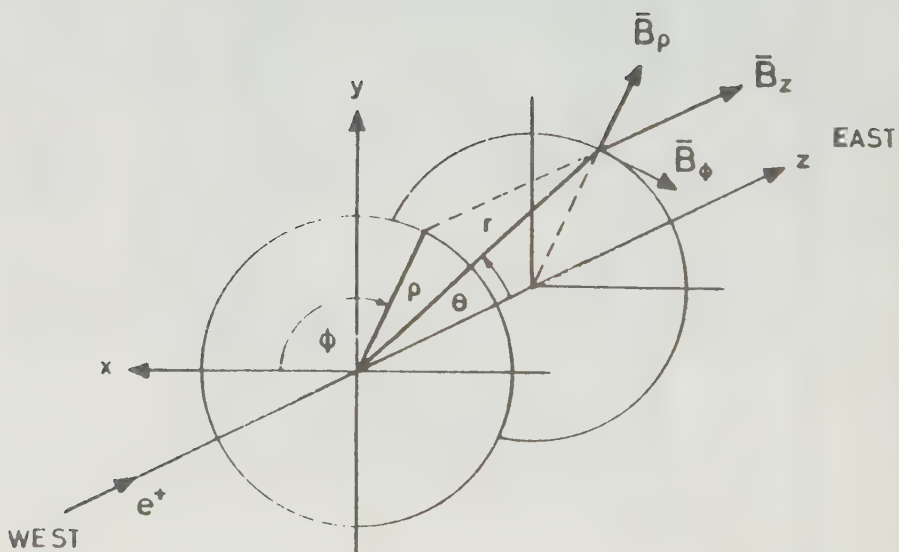


Fig. 2

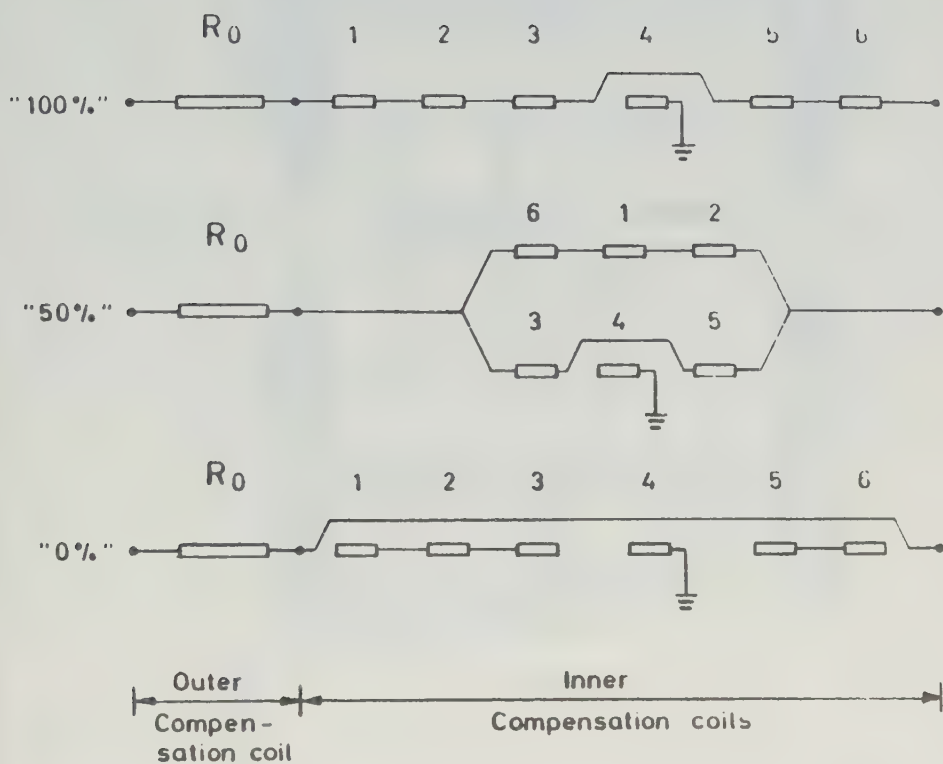
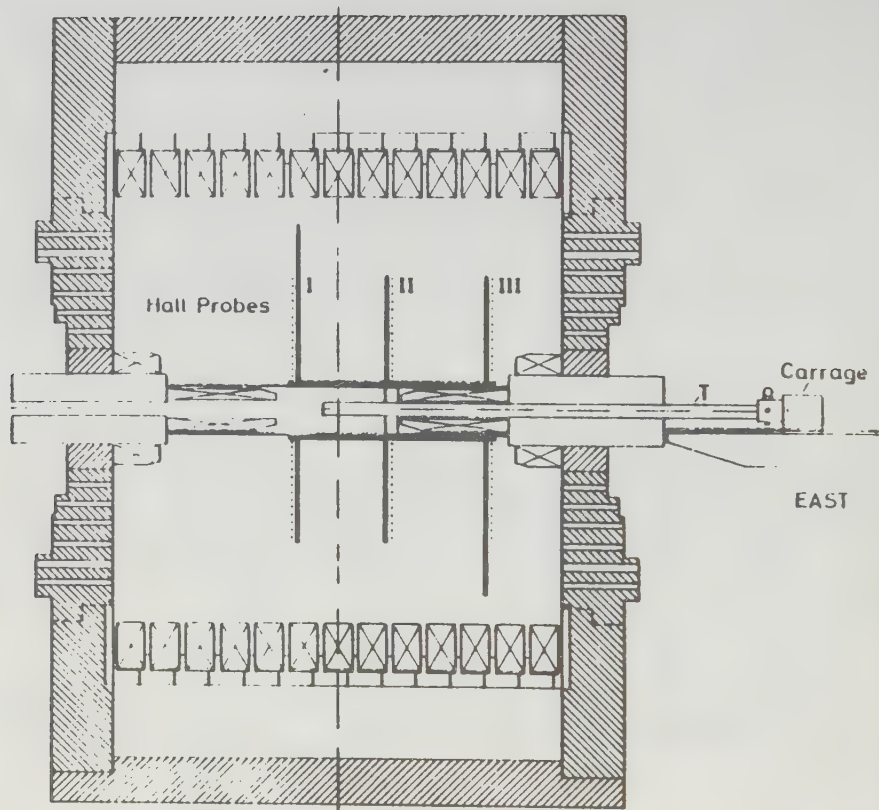
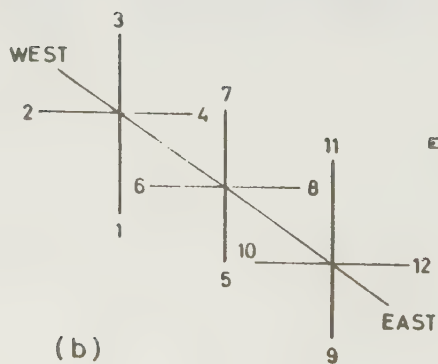


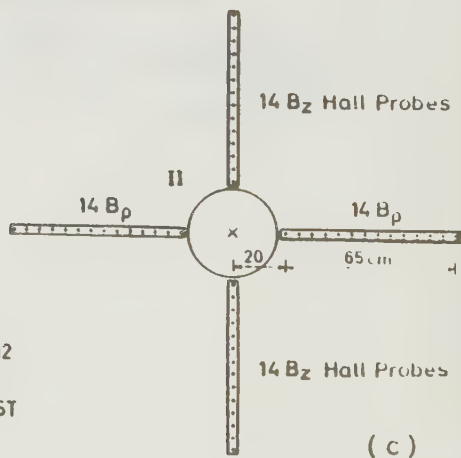
Fig. 3



(a)



(b)



(c)

Fig. 4

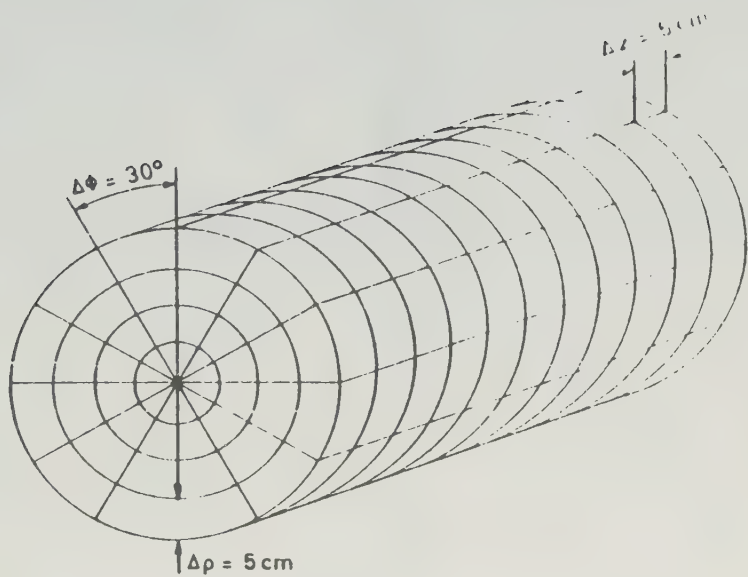


Fig. 5

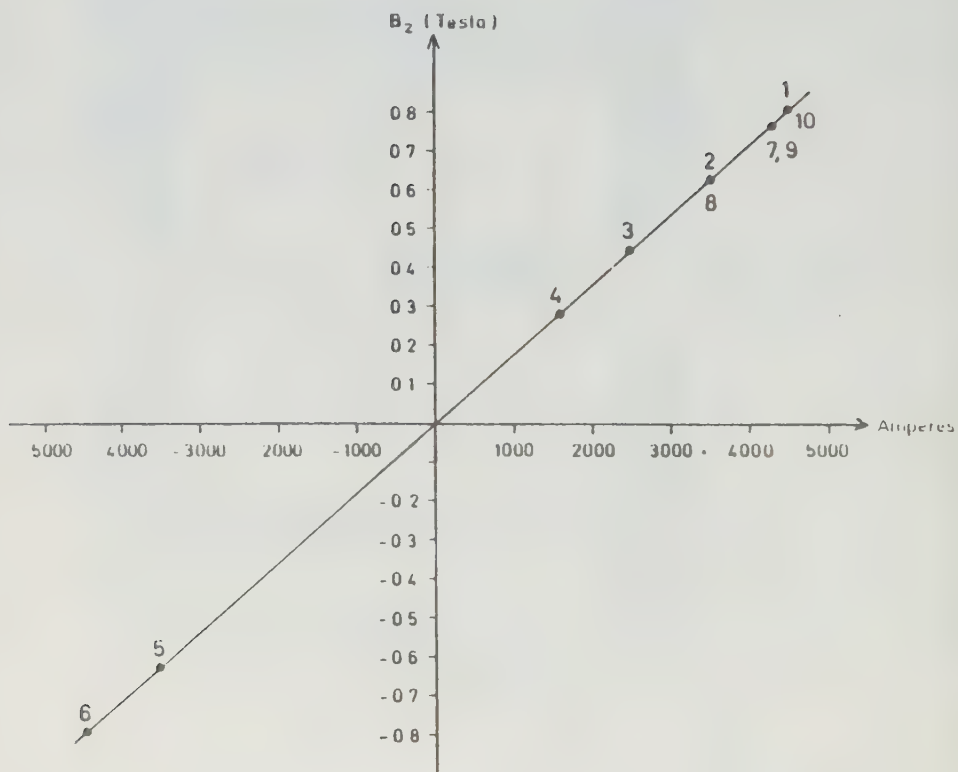


Fig. 6

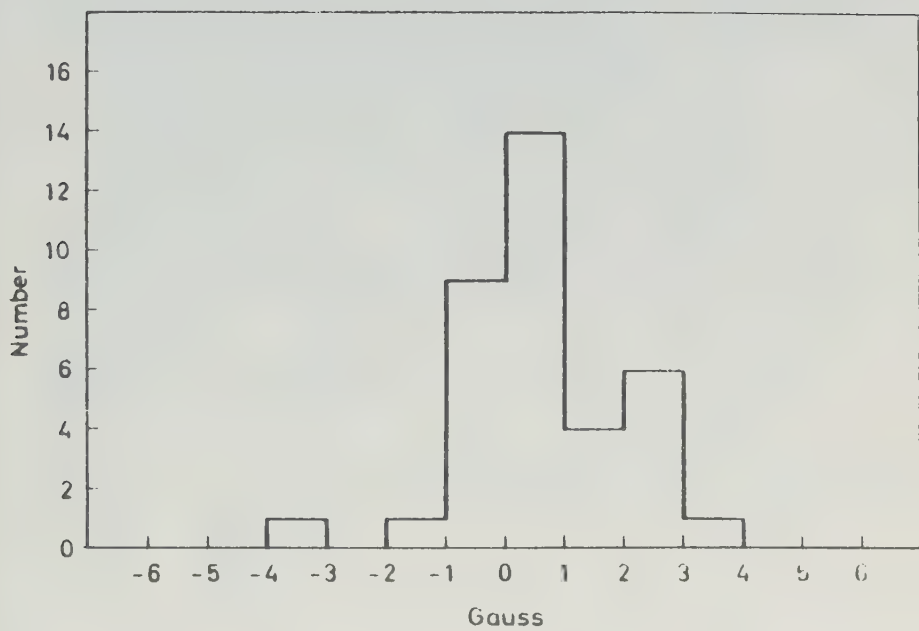


Fig. 7

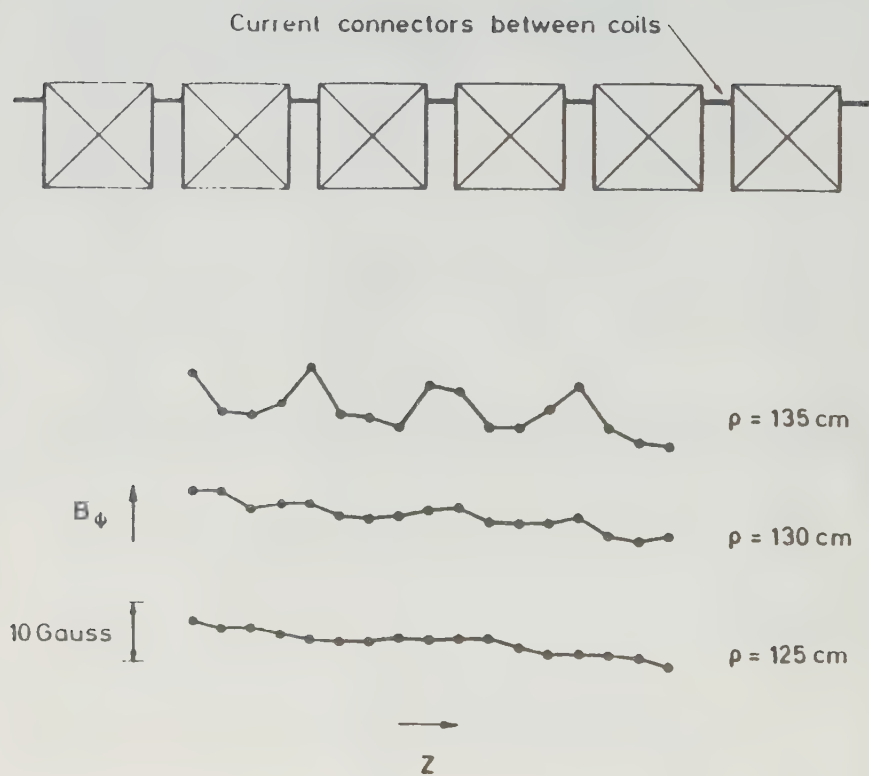


Fig. 8

32.0% compensation

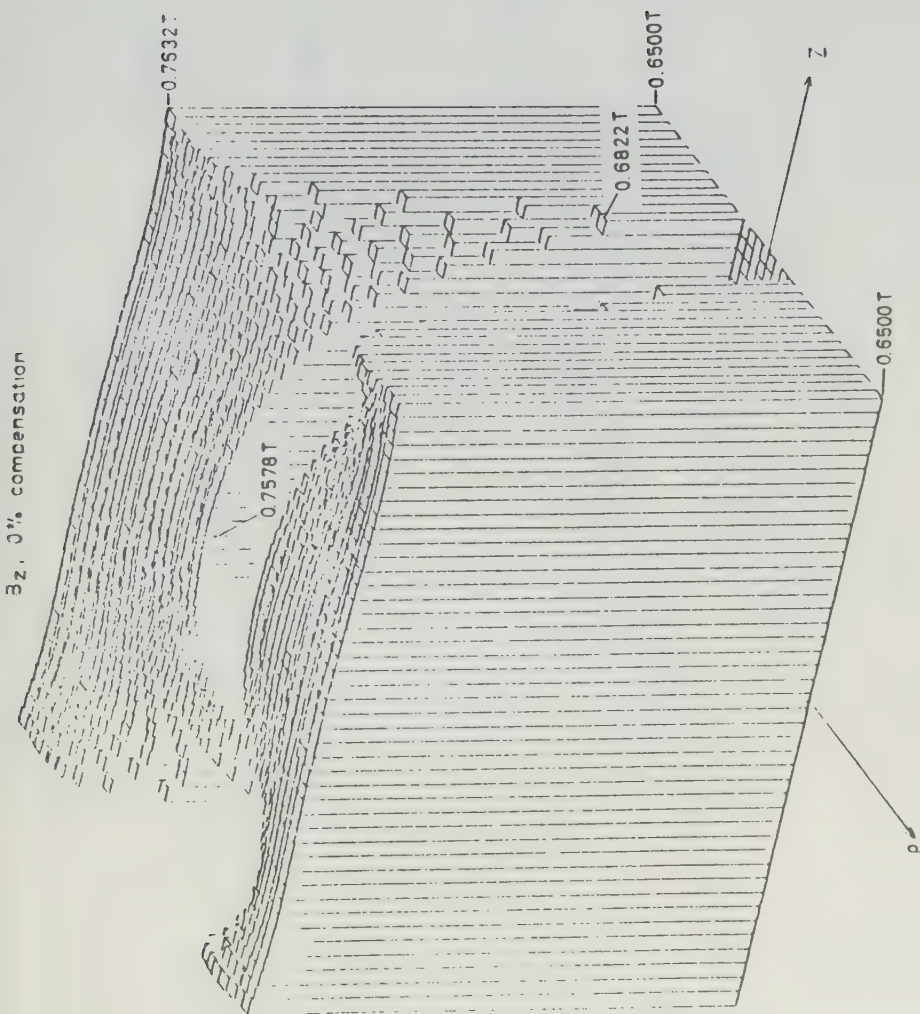


Fig. 9

3z, 50% compensation

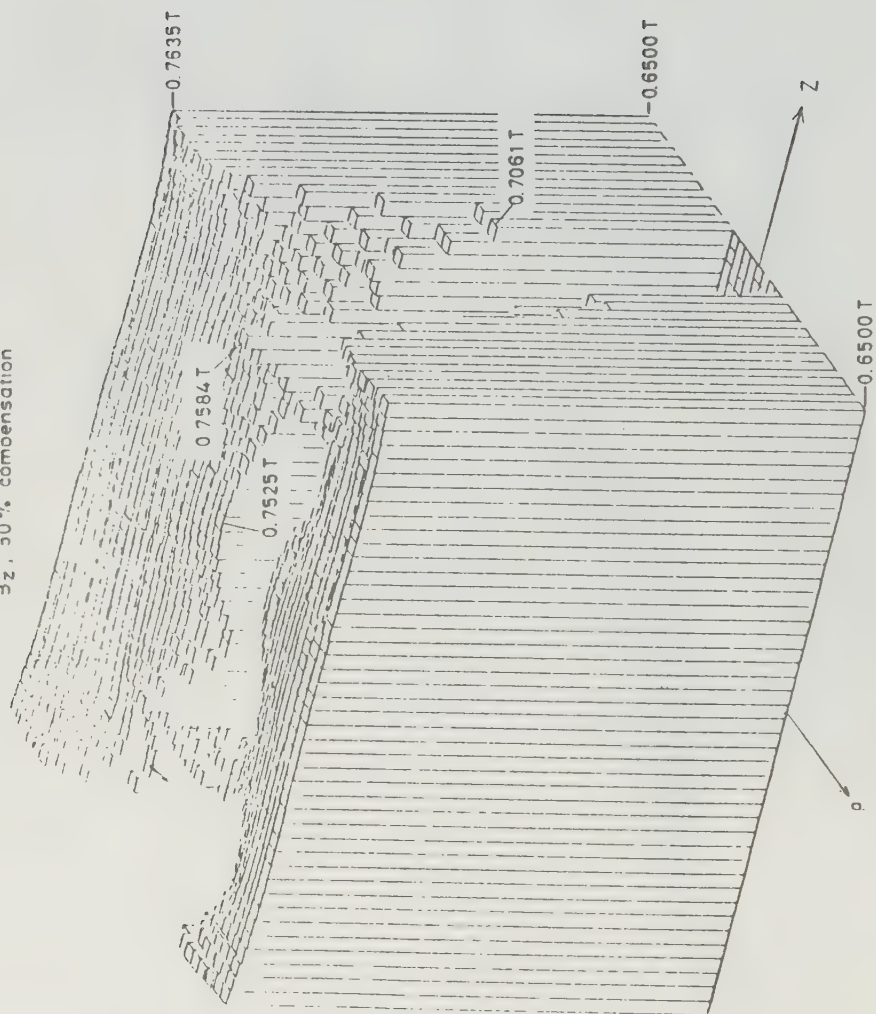


Fig. 10

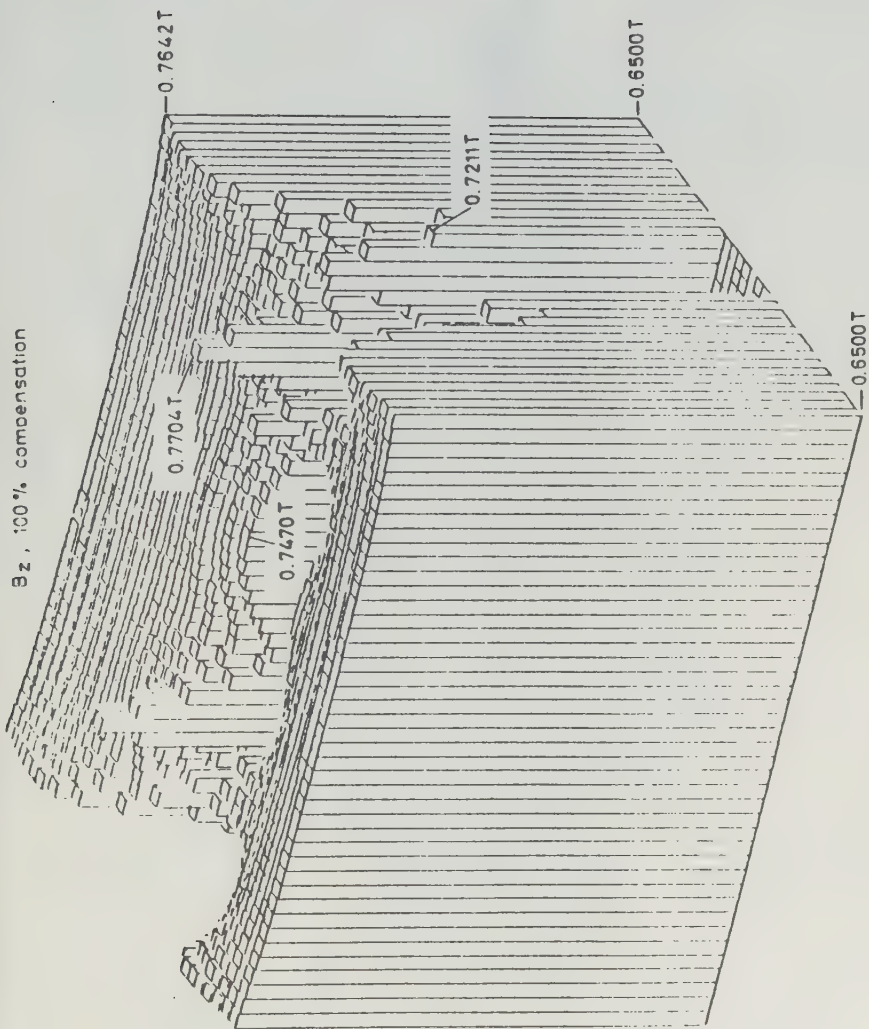


Fig. 11

$B_z, 0^\circ$, compensation

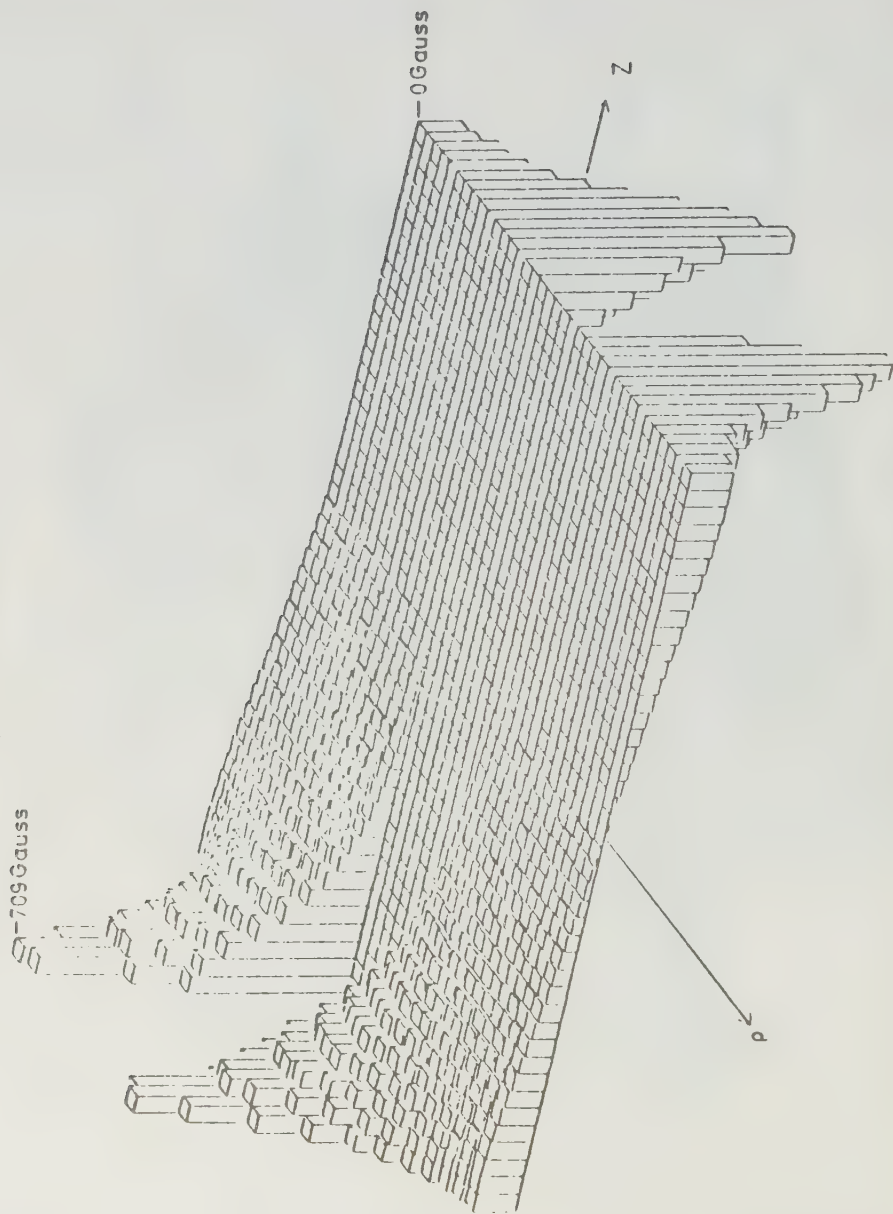
-709 Gauss

0 Gauss

z

p

Fig. 12



B_p , 50% compensation

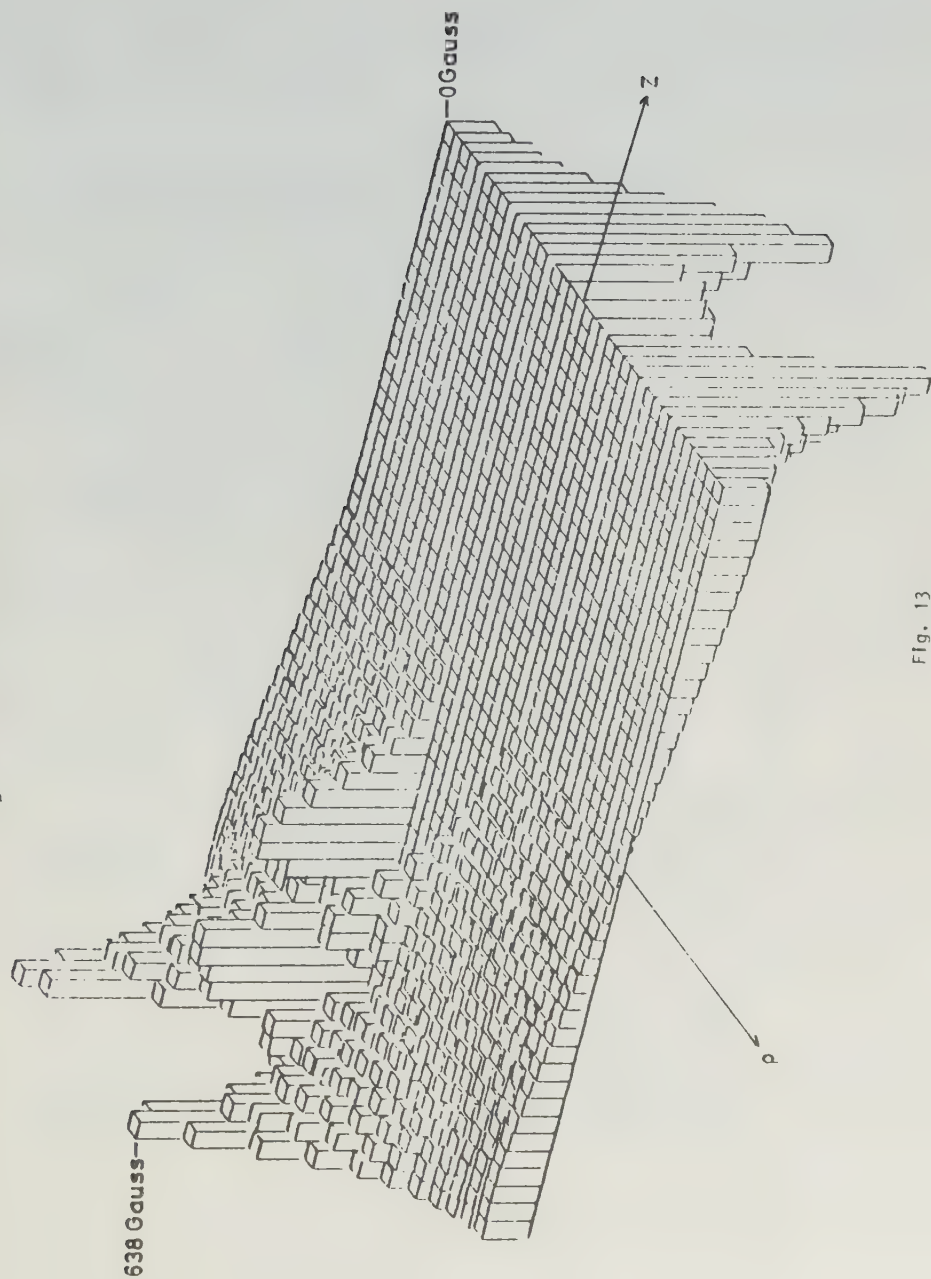


Fig. 13

B_p , 100% compensation

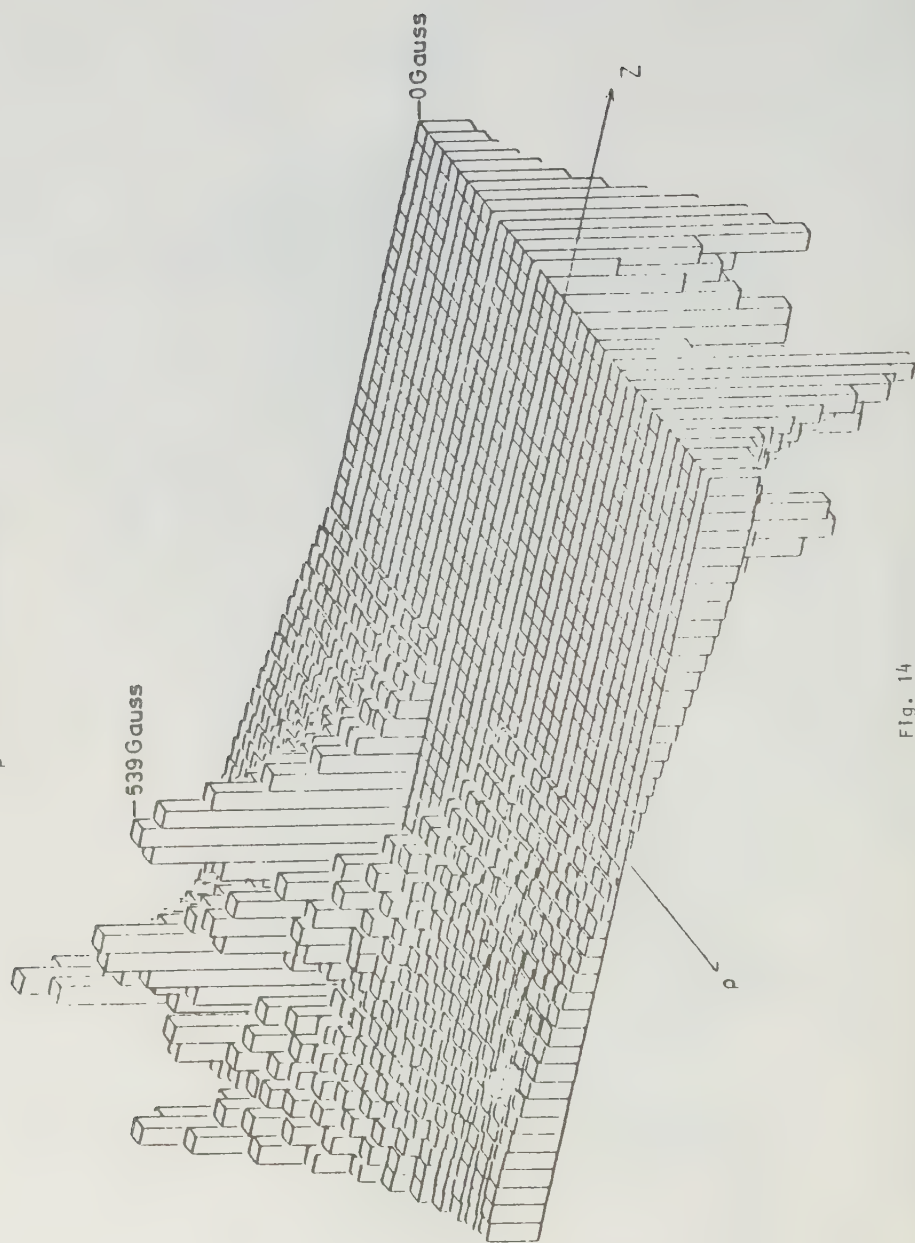


Fig. 14

SEARCH FOR FRACTIONALLY CHARGED PARTICLES PRODUCED IN e^+e^- ANNIHILATION

The ARGUS Collaboration

H. ALBRECHT, U. BINDER, G. HARDER, H. HASEMANN, A. PHILIPP,
W. SCHMIDT-PARZEFALL, H. SCHRÖDER, H.D. SCHULZ, R. WURTH

DESY, Hamburg, Germany

A. DRESCHER, B. GRÄWE, U. MATTHIESEN, H. SCHECK, J. SPENGLER, D. WEGENER

Institut für Physik, Universität Dortmund ¹, Dortmund, Germany

R. HELLER ², K.R. SCHUBERT, J. STIEWE, R. WALDI, S. WESELER

Institut für Hochenergiephysik, Universität Heidelberg ¹, Heidelberg, Germany

N.N. BROWN ³, K.W. EDWARDS ⁴, W.R. FRISKEN ⁵, Ch. FUKUNAGA ⁵, D.J. GILKINSON ⁶,
D.M. GINGRICH ⁶, M. GODDARD ⁵, P.C.H. KIM ⁶, R. KUTSCHKE ⁶, D.B. MACFARLANE ⁶,
J.A. McKENNA ⁶, K.W. McLEAN ³, A.W. NILSSON ³, R.S. ORR ⁶, P. PADLEY ⁶, P.M. PATEL ³,
J.D. PRENTICE ⁶, H.C.J. SEYWERD ⁶, B.J. STACEY ⁶, T.-S. YOON ⁶, J.C. YUN ⁴

Institute of Particle Physics ⁷, Canada

R. AMMAR, D. COPPAGE, R. DAVIS, S. KANEKAL, N. KWAK

University of Kansas ⁸, Lawrence, KS, USA

G. KERNEL, M. PLEŠKO

J. Stefan Institute and Department of Physics, University of Ljubljana ⁹, Ljubljana, Yugoslavia

P. BÖCKMANN ¹⁰, L. JÖNSSON, Y. OKU

Institute of Physics, University of Lund ¹¹, Lund, Sweden

M. DANILOV, V. LUBIMOV, V. MATVEEV, V. NAGOVITSIN, V. RYLTISOV, A. SEMENOV,
Yu. SEMENOV, V. SHEVCHENKO, V. SOLOSHENKO, V. SOPOV, I. TICHOMIROV,
Yu. ZAITSEV

Institute of Theoretical and Experimental Physics, Moscow, USSR

R. CHILDERS, C.W. DARDEN and H. GENNOW ¹²

University of South Carolina ¹³, Columbia, SC, USA

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A search has been made for particles with charge $Q = \frac{1}{3}$, $Q = \frac{2}{3}$ and $Q = \frac{4}{3}$ produced in e^+e^- annihilation using the ARGUS detector at the e^+e^- storage ring DORIS, operating at a centre of mass energy around 10 GeV. No candidate events were found in 84.5 pb^{-1} of collected data. Upper limits are established for the cross section for the production of fractionally charged particles with masses up to $4 \text{ GeV}/c^2$, improving on previously obtained limits.

For footnotes see next page

Since the formulation of the quark model [1], searches for free quarks have been made by many experiments [2-6]^{†1}, generally without success. It is therefore a common belief that the strong interaction, as formulated by quantum chromodynamics, causes quarks to be confined in hadrons. In the absence of a rigorous proof for this supposition, whenever improved tools become available, a search for fractionally charged particles should be performed. Electron-positron annihilation, having no hadrons in the initial state, would seem to be a reaction where one might favourably expect the production of free quarks.

We report here on a search for fractionally charged particles with charges $Q = \frac{1}{3}$, $Q = \frac{2}{3}$ and $Q = \frac{4}{3}$, using the ARGUS detector at the e^+e^- storage ring DORIS. Recently, quark searches in e^+e^- collisions have been performed by the JADE [3,7], Mark II [4], PEP4 [5], PEP14 [6] and OLYA^{‡2} collaborations. We have achieved an increased sensitivity by exploiting the capability of the ARGUS detector to precisely measure dE/dx energy loss of particle tracks with good pattern recognition, and because of the higher cross section for e^+e^- annihilation at DORIS, operating at centre of mass energies around 10 GeV. An important feature of our detector is that particles traverse only 1.2% of a nuclear interaction length from the vertex before being detected. This is less matter than in other detectors, due to the absence of a pressure vessel, re-

ducing the probability of quark absorption before detection. We also want to note that our data do not only originate from continuum e^+e^- reactions, but also from decays of the various T-states.

A description of the ARGUS detector has been previously published [9,10], so that only relevant features are summarized here. Charged particle tracks are measured by a cylindrical drift chamber in an 0.8 T magnetic field. The drift chamber is operated with a gas mixture consisting of 97% propane and 3% methylal at atmospheric pressure. A particle track is measured by 36 concentric cylindrical layers of 18 mm thickness. In each layer the track coordinate and energy loss are measured. The truncated average dE/dx for a track is calculated by discarding the highest lying 30% and lowest lying 10% of the energy loss measurements. The dE/dx measurement thus obtained corresponds to the most probable energy loss. Bhabha scattering events are used for calibration. The resulting resolutions are for the track momentum:

$$\sigma_p/p = [0.01^2 + 0.01^2(p/(\text{GeV}/c))^2]^{1/2},$$

and for the dE/dx energy loss, in longterm average:

$$\sigma(dE/dx)/(dE/dx) = 0.05.$$

The dE/dx resolution function is closely approximated by a gaussian distribution over more than 3 orders of magnitude.

The search for fractionally charged particles with charge Q was made using the following relation for the energy loss:

$$dE/dx = (Q^2/\beta^2)f(\beta).$$

The function $f(\beta)$ contains only constants, except for the particle velocity β , which depends on the particle mass, m_q :

$$\beta = p/(p^2 + m_q^2)^{1/2}.$$

The momentum measurement gives only the apparent momentum, p_a , which is related to the true momentum by:

$$p = Qp_a.$$

Thus, the quark charge Q is determined by a measurement of p_a and dE/dx , if the quark mass m_q is known or assumed. Furthermore, an observation of a dE/dx value smaller than that for minimum ionizing tracks can only result from quarks. The most probable ener-

¹ Supported by the Bundesministerium für Forschung und Technologie, Fed. Rep. Germany.

² Present address: DESY, Hamburg, Fed. Rep. Germany.

³ McGill University, Montreal, Canada.

⁴ Carleton University, Ottawa, Canada.

⁵ York University, Downsview, Canada.

⁶ University of Toronto, Toronto, Canada.

⁷ Supported by the Natural Sciences and Engineering Research Council, Canada.

⁸ Supported by the US National Science Foundation and a University of Kansas Faculty Improvement award.

⁹ Supported in part by the Internationales Büro KfA, Jülich and DESY, Hamburg, Fed. Rep. Germany.

¹⁰ Present address: CERN, Geneva, Switzerland.

¹¹ Supported by the Swedish Research Council.

¹² On leave of absence from the University of Stockholm, Stockholm, Sweden.

¹³ Supported by the US Department of Energy, under contract DE-AS09-80ER10690.

^{†1} Recent JADE results are reported in ref. [7].

^{‡2} Recent OLYA results on exclusive quark production are reported in ref. [8].

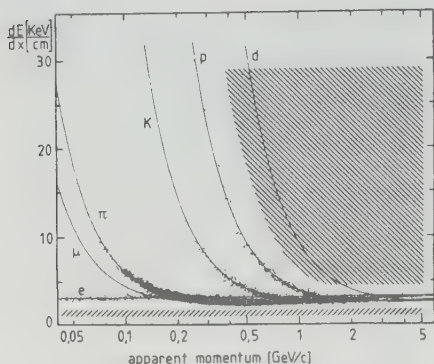


Fig. 1. Regions in the dE/dx - p_a plane used in the free quark search are shown in the hatched areas. The dE/dx measurements from a sample of positively and negatively charged tracks representing about 1% of the data set illustrate the separation of the various particle types.

gy loss for minimum ionizing $Q = 1$ particles is 2.5 keV/cm in the gas mixture used.

The quark search was performed in two regions of energy loss and apparent momentum which are not populated by the known $Q = 1$ particles. These regions are shown in fig. 1. They are defined as:

Lower region:

$$0.875 \text{ keV/cm} \leq dE/dx \leq 1.5 \text{ keV/cm}.$$

Upper region:

$$4.0 \text{ keV/cm} \leq dE/dx \leq 27.5 \text{ keV/cm}.$$

The upper region was further bounded by requiring that, for any apparent momentum, dE/dx be larger than that for a $Q = 1$ particle with mass $1.41 \text{ GeV}/c^2$.

The quark search in the upper region was made in inclusive multihadron events, $e^+e^- \rightarrow qX$, as well as in exclusive two-body events, $e^+e^- \rightarrow q\bar{q}$. However, only negatively charged tracks were examined, in order to exclude contamination by fragments from beam-gas or beam-wall interactions. The number of dE/dx samples was required to be larger than 15 after truncation, to insure good dE/dx resolution. Tracks were rejected where $\sigma(dE/dx)$ exceeded 7%, or the track fit probability was less than 1%. These last two requirements eliminate most overlapping and fake tracks.

In the lower region, both charge signs were admitted, but only multihadron events were used, because the trigger efficiency of the detector for the two-body quark channel is small and not precisely known. Here at least 7 dE/dx samples and a dE/dx resolution of better than 18% were required to accept a track. For both regions, only tracks with a polar angle θ such that $|\cos \theta| \leq 0.7$ were considered.

Data taken at various centre of mass energies on and off Υ resonances have been used for this search. The corresponding integrated luminosities and numbers of events obtained are listed in table 1. Multihadron events were selected according to the standard ARGUS procedure [9]. They represent a complete and unbiased inclusive data set for events with 3 or more detected tracks.

The two-prong events consist mainly of muon pairs, tau pairs and events from $\gamma\gamma$ reactions. Events are accepted if they contain just 2 oppositely charged tracks whose origin deviates from the interaction point by less than 6 cm in the beam direction, and less than 1.5 cm radially. If at least one track has momentum less than 2 GeV/c or the event has less than 0.6 GeV energy in the shower counters, no further requirements are made. Failing this, in order to suppress Bhabha scattering events, the remaining two-prong events were required to have at least one track with a polar angle such that $|\cos \theta| < 0.866$, and to satisfy, in addition, at least one of the following: (1) at least one track with shower energy $E_s < 1.5 \text{ GeV}$, (2) at least one track with momentum $p < 3 \text{ GeV}/c$ and $E_s < 4 \text{ GeV}$, (3) acollinearity between the two tracks larger than 15° , or (4) energy loss incompatible with an electron assignment, that is $dE/dx < 2 \text{ keV/cm}$ or $dE/dx > 4.4 \text{ keV/cm}$.

Table 1

	$L [\text{pb}^{-1}]$	Selected multihadron events ($\times 10^3$)	Selected two-prong events ($\times 10^3$)
$\Upsilon(1S)$	23.6	321	278
$\Upsilon(2S)$	38.6	309	440
$\Upsilon(4S)$	10.0	53	65
continuum	12.3	46	98
total	84.5	729	881

Using the events thus obtained, and applying the quark track search criteria discussed above, no quark candidate was found in the lower search region with small dE/dx . In the upper dE/dx region, 25 candidates were observed. Of these, 6 were clearly identified as the production of antideuterons in e^+e^- [11].

A further 18 events, we attribute to overlapping tracks of electrons in Bhabha scattering events with a bremsstrahlung photon, which converts into an electron-positron pair: that is $e^+e^- \rightarrow e^+e^-\gamma$ followed by $\gamma \rightarrow e^+e^-$. This interpretation is supported by the following observations. The events apparently have three prongs: charge conservation demands an additional track with the same charge as the candidate track. The energy loss of the candidates is twice that expected for an electron. The time-of-flight measurement is consistent with $\beta = 1$ for the candidate tracks. The energy deposited in the shower counters corresponds to twice the momentum of the candidate track. Momentum balance demands another track with approximately the same momentum as the candidate track. Thus, by using all detector information available, these tracks can confidently be identified as overlapping electrons.

The remaining one event contains a track which can be explained as the overlap of two hadron tracks. Again, charge conservation demands one more track of the same charge as the candidate track. Also, the energy loss is twice that for that of a pion, the time-of-flight measurement is consistent with a fast pion track and the energy deposited in the shower counters is consistent with two overlapping hadrons. The transverse momentum balance, using photons and charged tracks, requires an additional particle with $p_T = 1.27$ GeV/c at an azimuth of $\phi = 2.47$ rad. The candidate track has $p_T = 1.03$ GeV/c at $\phi = 2.51$ rad, corresponding well, within errors, to the missing p_T . Therefore this track can also be rejected as an overlap. We conclude that no free quarks have been observed.

In order to convert this result into an upper limit for the cross section for quark production, $\sigma_q(e^+e^- \rightarrow qX)$, we use the definition for the 90% confidence level from Poisson statistics:

$$\sum_i L_i \sigma_q^{\text{vis}} = 2.3.$$

The sum is extended over the various beam energies, where the integrated luminosities, L_i , were accumu-

lated. The visible cross section, σ_q^{vis} is related to the true cross section by

$$\frac{\sigma_q^{\text{vis}}}{\sigma_q} = \int^R \frac{d\sigma_q}{dp} \epsilon(p, Q, m_q) dp \bigg/ \int^R \frac{d\sigma_q}{dp} dp.$$

The integral is performed in the $dE/dx-p_a$ plane with the assumed quark mass and charge kept constant. Only those momenta p_a for which dE/dx lies inside one of the regions R of search contribute to the integral. The finite dE/dx resolution has been taken into account at the boundaries of the regions. Two extreme forms were taken for the momentum distribution, $d\sigma_q/dp$, of the produced quarks:

$$\text{Model I: } d\sigma_q/dp \propto p^2/E,$$

and

$$\text{Model II: } d\sigma_q/dp \propto (p^2/E) \exp(-3.5 E/\text{GeV}),$$

as previously suggested by the JADE collaboration [3]. The function $\epsilon(p, Q, m_q)$ represents the detection efficiency for a free quark as a function of its momentum, charge and mass. This efficiency is composed of many factors: the trigger efficiency, the geometrical acceptance, the track reconstruction efficiency and the efficiency for the applied selection cuts. All of these factors were carefully determined by an analysis of data supplemented by Monte Carlo studies. In particular, the track reconstruction efficiency in the lower region of dE/dx was determined by running the drift chamber with reduced high voltage.

Finally, we relate the quark production cross section to the cross section for muon pair production and quote our result as a limit on

$$R_q = \sigma(e^+e^- \rightarrow qX)/\sigma(e^+e^- \rightarrow \mu^+\mu^-).$$

The result is shown in fig. 2, together with previously reported limits [3–7]. In the case $Q = \frac{2}{3}$, or $Q = \frac{4}{3}$ particles, the limits can be extended to quark masses below those shown in fig. 2. At $m_q = 1$ MeV/c², the limits on R_q are respectively 1.1×10^{-4} and 0.65×10^{-4} for model I, and 0.50×10^{-4} and 1.1×10^{-3} for model II.

We conclude that we have obtained a significantly improved sensitivity for the observation of free quarks which reaches the level of 10^{-4} in R_q . Cross section limits are presented for free quark production with quark masses less than 4 GeV/c². No free quarks were observed.

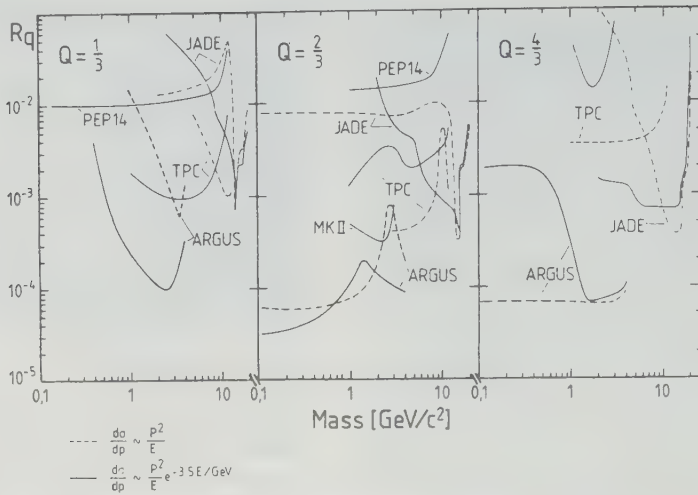


Fig. 2. Upper limits at the 90% confidence level for the production of particles with charge $Q = \frac{1}{3}$, $Q = \frac{2}{3}$ and $Q = \frac{4}{3}$ in e^+e^- annihilation are shown for two different assumptions concerning their momentum spectrum. Also shown are previously reported limits from other e^+e^- experiments [3-7].

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OBSERVATION OF ANTIDEUTERON PRODUCTION IN ELECTRON-POSITRON ANNIHILATION AT 10 GeV CENTER OF MASS ENERGY

The ARGUS Collaboration

H. ALBRECHT, U. BINDER, G. HARDER, H. HASEMANN, A. PHILIPP,
W. SCHMIDT-PARZEFALL, H. SCHRÖDER, H.D. SCHULZ, R. WURTH

DESY, Hamburg, Fed. Rep. Germany

A. DRESCHER, B. GRÄWE, U. MATTHIESEN, H. SCHECK, J. SPENGLER, D. WEGENER

Institut für Physik, Universität Dortmund ¹, Dortmund, Fed. Rep. Germany

R. HELLER ², K.R. SCHUBERT, J. STIEWE, R. WALDI, S. WESELER

Institut für Hochenergiephysik, Universität Heidelberg ¹, Heidelberg, Fed. Rep. Germany

N.N. BROWN ³, K.W. EDWARDS ⁴, W.R. FRISKEN ⁵, Ch. FUKUNAGA ⁵, D.J. GILKINSON ⁶,
D.M. GINGRICH ⁶, M. GODDARD ⁵, P.C.H. KIM ⁶, R. KUTSCHKE ⁶, D.B. MACFARLANE ⁶,
J.A. McKENNA ⁶, K.W. McLEAN ³, A.W. NILSSON ³, R.S. ORR ⁶, P. PADLEY ⁶, P.M. PATEL ³,
J.D. PRENTICE ⁶, H.C.J. SEYWERD ⁶, B.J. STACEY ⁶, T.-S. YOON ⁶, J.C. YUN ⁴

Institute of Particle Physics ⁷, Canada

R. AMMAR, D. COPPAGE, R. DAVIS, S. KANEKAL, N. KWAK

University of Kansas ⁸, Lawrence, KS, USA

G. KERNEL, M. PLEŠKO

J. Stefan Institute and Department of Physics, University of Ljubljana ⁹, Ljubljana, Yugoslavia

P. BÖCKMANN ¹⁰, L. JÖNSSON, Y. OKU

Institute of Physics, University of Lund ¹¹, Lund, Sweden

M. DANILOV, V. LUBIMOV, V. MATVEEV, V. NAGOVITSIN, V. RYLTISOV, A. SEMENOV,
Yu. SEMENOV, V. SHEVCHENKO, V. SOLOSHENKO, V. SOPOV, I. TICHOMIROV,
Yu. ZAITSEV

Institute of Theoretical and Experimental Physics, Moscow, USSR

R. CHILDERS, C.W. DARDEN and H. GENNOW ¹²

University of South Carolina ¹³, Columbia, SC, USA

Received 22 April 1985

The production of antideuterons has been observed in electron-positron annihilations at center-of-mass energies around 10 GeV. Antideuterons have been identified unambiguously by their energy loss in the drift chamber, their time-of-flight and the pattern of their energy deposition in the shower counters of the ARGUS detector. The production rate in the momentum range (0.6–1.8) GeV/c is $(1.6^{+1.0}_{-0.7}) \times 10^{-5}$ per hadronic event

1. Introduction. The investigation of baryon production in hard interactions has recently become of great experimental [1–5] and theoretical [6–12] interest. A deeper understanding of parton fragmentation is expected to result from these studies since baryons, due to their high mass, reflect more details of the earlier stages of the fragmentation process [13] than the copiously produced mesons. The latter turn out to be dominantly decay products of heavier resonances [14] and therefore reveal only indirect information on parton fragmentation.

Whereas the production of quark–antiquark pairs in electron–positron annihilation is a common feature of all fragmentation models, their descriptions of baryon production differ significantly. Data of higher precision, correlation studies and the investigation of as many baryon channels as possible should allow one to differentiate between the various approaches to parton fragmentation. In this letter we report on the first observation of antideuteron production in electron–positron annihilation, which leads to insight into the production of correlated antibaryon pairs of small relative momentum. A corresponding search for deuteron production in electron–positron annihilation is not possible, since in a significant fraction of beam gas events deuterons are produced. Moreover, the pulse height distribution in the shower counters only allows one to differentiate antideuterons from other hadrons.

The data were collected with the ARGUS detec-

tor at the DORIS II storage ring at DESY. The center-of-mass energies ranged from 9.4 to 10.6 GeV. The detector, its trigger and particle identification capabilities are described in ref. [15]. The event sample used in the analysis corresponds to an integrated luminosity of 23.6 pb^{-1} on the $\Upsilon(1S)$, 38.6 pb^{-1} on the $\Upsilon(2S)$, 14.7 pb^{-1} on the $\Upsilon(4s)$ and 7.6 pb^{-1} in the continuum region.

2. Selection of antideuterons. The selection of antideuterons was performed in several steps. As a first step two samples of annihilation events were selected according to the following criteria:

events with ≥ 3 charged tracks coming from the vertex
or

events with ≥ 3 charged tracks which are not necessarily produced at the interaction vertex but have an energy of $\geq 1.7 \text{ GeV}$ detected by the shower counters. 728517 events passed these selection criteria. Next, for each event negative particles with $|\cos \theta| < 0.7$ originating from the interaction vertex with at least 15 samplings of energy loss in the drift chamber after truncation were selected. In this way an optimal momentum and energy loss determination was secured. In a further selection step the following cuts were applied to select antideuteron candidates:

(i) Truncated energy loss $dE/dx \geq 4 \text{ keV/cm}$. This corresponds to more than six standard deviations from the energy loss of high momentum electrons (fig. 1a). Note that the energy loss distribution of particles of given momentum has a gaussian shape as demonstrated by fig. 1b.

(ii) The measured energy loss had to be larger than that expected for a particle of mass $M = 1.41 \text{ GeV}/c^2$, unit charge and the momentum measured.

(iii) The standard deviation of the individual energy loss for a track had to be less than 7% of the mean energy loss. This cut rejects tracks which partly overlap with another track or with background hits.

(iv) The track fit probability had to be larger than 1%. This cut removes overlapping and not properly reconstructed tracks. It should be mentioned, however, that the experimental χ^2 distribution of the track fit deviates considerably from the theoretical one at large values of χ^2 . The number of tracks rejected by this cut was larger than 1% and varied for different running periods.

¹ Supported by the Bundesministerium für Forschung und Technologie, Fed. Rep. Germany.

² Present address: DESY, Hamburg, Fed. Rep. Germany.

³ McGill University, Montreal, Canada.

⁴ Carleton University, Ottawa, Canada.

⁵ York University, Downsview, Canada.

⁶ University of Toronto, Toronto, Canada.

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¹⁰ Present address: CERN, Geneva, Switzerland.

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After these selection steps, 16 candidate tracks remained. They were visually scanned. Nine of them turned out to be radiative Bhabha events where the photon converted into an electron–positron pair before entering the drift chamber. The electron track from this pair and the original electron overlapped completely and produced twice the ionization energy loss. This was established by the following observations, valid for all nine events:

(1) The particle with high dE/dx was accompanied by a positron going in exactly the same direction and by a positron going in the opposite direction. The net charge of the event was thus $+1$.

(2) The energy deposited in the shower counters coincided within errors, with the center-of-mass energy. The lateral shape of the showers corresponded to the shape of an electromagnetic shower [16].

(3) The missing momentum of the event was within error limits equal to the momentum of the antideuteron candidate.

(4) The time-of-flight information excluded particle velocities $\beta < 0.8$ while the dE/dx information required $\beta < 0.8$.

A Monte Carlo calculation [17] shows that (12 $\pm$ 3) events of this type are expected.

One track with high dE/dx was interpreted as an overlap of two particles in a multihadron event because of the following observations:

(a) The missing p_T in the event coincided with the p_T of this track ($\Delta\phi = 0.04$, $\Delta p_T = 0.24$ GeV/c).

(b) The time-of-flight corresponds to a fast particle ($\beta = 1 \pm 0.036$), while the ionization loss was approximately 2 times that for a relativistic particle. The χ^2 for the π^- , K^- , $\bar{p}$ and antideuteron hypothesis was large.

(c) The energy deposited by this track in the shower counters was consistent with that expected from two minimum ionizing particles.

This leaves us with six events containing antideuteron candidate tracks. In these events the setting of the magnetic field, the raw information of all ADC channels, including applied corrections, as well as the time-of-flight and shower counter information were carefully verified.

In fig. 1a the energy loss and the momentum of each antideuteron candidate track are entered. The observed energy loss is in good agreement with that expected for antideuterons.

The antideuteron hypothesis of the six candidates may be checked using the time-of-flight information and the pattern of the energy deposition in the shower counters. The information from the time-of-flight system is compatible with the antideuteron assignment. In three cases the masses are directly measurable ($m_{\bar{d}} = (1.86 \pm 0.07)$ GeV/ c^2 , (1.99 ± 0.13) GeV/ c^2 , (1.86 ± 0.12) GeV/ c^2). For the three other antideuteron candidates, double hits, backscattering due to annihilation of the antideuteron in the shower counters and too high pulse height in the time-of-flight counters respectively prevented the determination of the mass, but the time-of-flight information signalled a slow particle. In each of the six candidate events, the observed energy resulting from the annihilation in the shower counters was compatible with that expected for an antideuteron: the measured energy from the annihilation and the number of neighbouring shower counters set (cluster size) were larger than that observed for all other hadrons, including antiprotons (fig. 2a). Moreover, a pronounced albedo was observed in the drift chamber (fig. 2b); as expected, if the annihilation of a stopped antideuteron takes place in the shower counters.

These three independent methods of identifying the antideuteron are supplemented by the observation that in each of the six events with an antideuteron track at least one proton candidate track was detected. In three of these events at least one unambiguously identified proton track was observed. This may be compared with the measured rate of about 0.2 (anti) protons per hadronic event [1,2] in electron–positron annihilation at $\sqrt{s} = 10$ GeV.

3. Results and discussion. In order to calculate the production cross section from the number of observed antideuterons the acceptance was calculated. It includes the track and the vertex reconstruction efficiency, the antideuteron absorption, the trigger efficiency and the efficiency of the dE/dx and time-of-flight measurements. The geometrical acceptance was calculated assuming a flat angular distribution. The overall efficiency to detect an antideuteron is 0.55. Using the measured luminosity we arrive at the Lorentz invariant cross section

$$Ed^3\sigma/d^3p = (3.1^{+3.9}_{-1.7}) \times 10^{-5} \text{ nb/GeV}^2$$

$$\text{for } 1.97 \text{ GeV} \leq E_{\bar{d}} \leq 2.29 \text{ GeV}$$

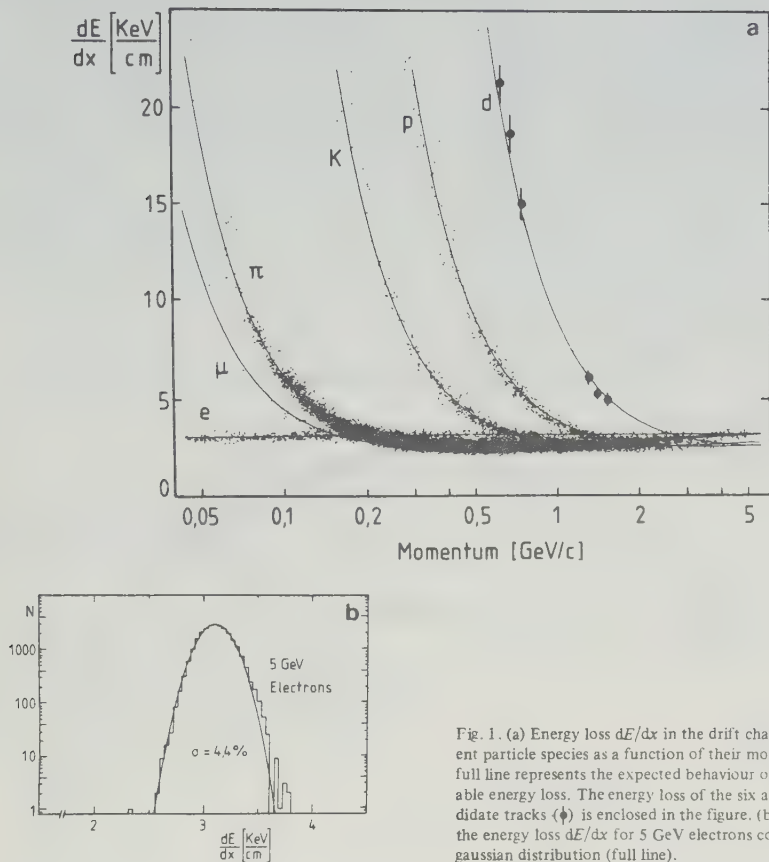


Fig. 1. (a) Energy loss dE/dx in the drift chamber for different particle species as a function of their momentum. The full line represents the expected behaviour of the most probable energy loss. The energy loss of the six antideuteron candidate tracks (Φ) is enclosed in the figure. (b) Distribution of the energy loss dE/dx for 5 GeV electrons compared to a gaussian distribution (full line).

and

$$Ed^3\sigma/d^3p = (2.0^{+2.0}_{-1.0}) \times 10^{-5} \text{ nb/GeV}^2$$

$$\text{for } 2.29 \text{ GeV} \leq E_{\bar{d}} \leq 2.6 \text{ GeV}$$

for the production of antideuterons. These cross sections correspond to a production rate in the energy range $1.97 \text{ GeV} \leq E_{\bar{d}} \leq 2.6 \text{ GeV}$ of $(1.6^{+1.0}_{-0.7}) \times 10^{-5}$ per hadronic event.

The results are compared in fig. 3 to the produc-

tion cross sections for $(\pi^+ + \pi^-)$ - and $(K^+ + K^-)$ -mesons and twice that for antiprotons [1]. Within a factor of 2 the latter cross sections coincide, while the production cross section for antideuterons is suppressed by two orders of magnitude. With the limited statistics of six antideuterons (3 from $\Upsilon(2S)$ -, 2 from $\Upsilon(1S)$ - and 1 from $\Upsilon(4S)$ -energy region), it is not possible to decide whether they come primarily from the three gluon decays or from continuum production.

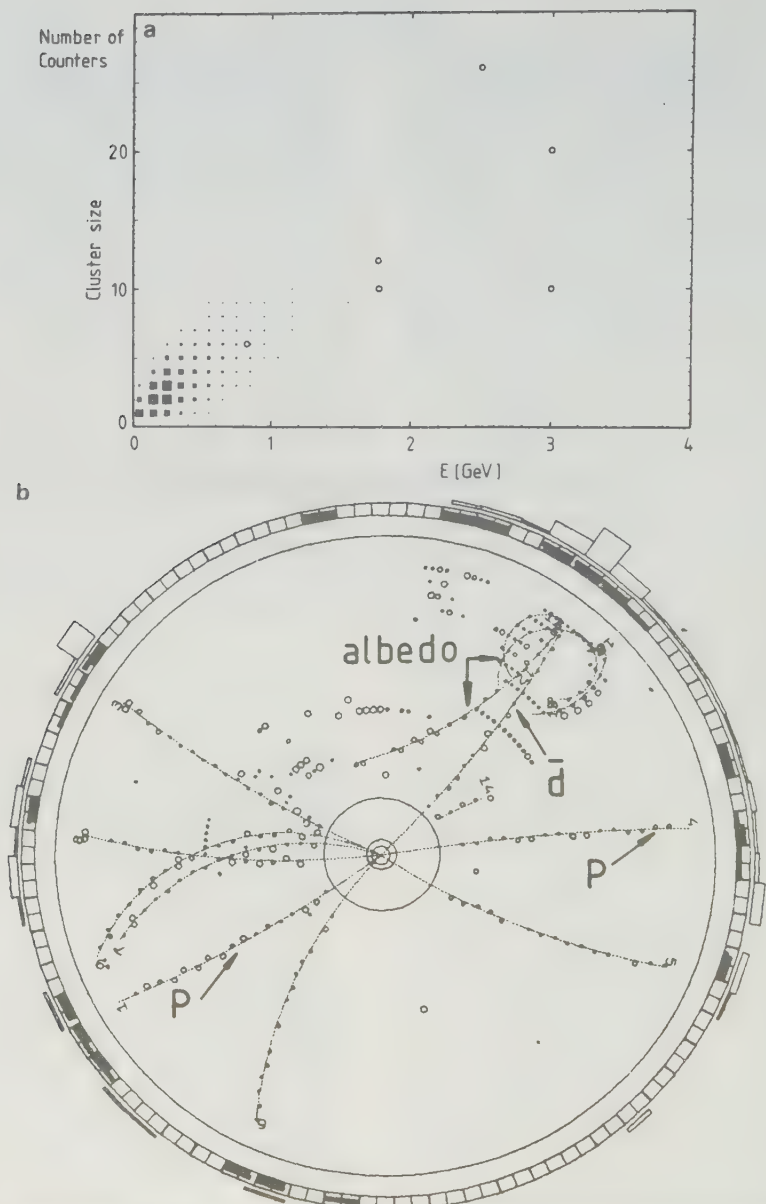


Fig. 2. (a) Energy deposition E in the shower counters versus cluster size for normal hadronic tracks (●) and the six antideuteron candidate tracks (○). The energy of the backscattered hadrons (not included in E) is especially high for those three candidate tracks with the smaller energy deposition E . The area of the black dots is proportional to the number of entries, the smallest area corresponds to one hadronic track. (b) One event with hits in the drift chamber projected to a plane transverse to the primary beams. The antideuteron track, its albedo and the two proton candidates of the event are labelled.

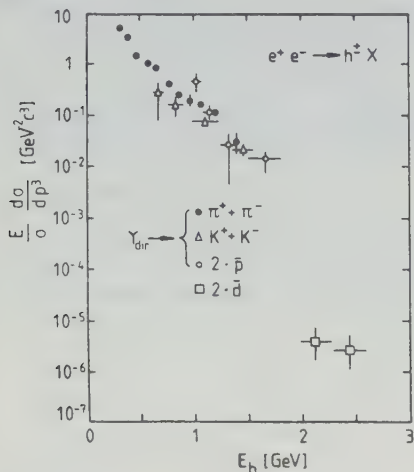


Fig. 3. Measured Lorentz invariant cross section for antideuteron production as a function of the particle energy. The results are compared with those for $\pi^\pm$, $K^\pm$ - and $2\bar{p}$ production (DASP II Collaboration [1]).

We have compared the main features of the events containing an antideuteron with those of other hadronic events. Within the large statistical errors no difference in the mean charged multiplicity, the event shape measures or the momentum distribution is observed. The only difference observed is the (expected) increase of proton production in events with an antideuteron track.

In view of the large spatial extension of the antideuteron, its production rate in hard electron-positron annihilations seems to be unexpectedly large. But it is interesting to observe that the rate of antideuteron production

$$r = (N_{\bar{d}}/N_{\pi^-})/(N_{\bar{p}}/N_{\pi^-})^2$$

as measured in this experiment

$$r \approx 2 \times 10^{-3}$$

is of the same order of magnitude as the one observed in proton-nucleon interactions [18] in a broad interval of center-of-mass energies

$$r \approx 5 \times 10^{-3}.$$

The latter observation was interpreted semiquantitatively by a model of Dorfan et al. [19] in which two antinucleons are produced independently in the interaction and form an antideuteron when their wave functions overlap, the antideuteron production rate thus being a measure of antibaryon production at small relative momenta. It is tempting to generalize this model to antideuteron production in electron-positron annihilation.

In summary, we have detected the production of six antideuterons in electron-positron annihilation at $\sqrt{s} = 10$ GeV. Three independent components of the ARGUS detector have been used to identify the antideuterons. The expected higher proton production rate in events containing an antideuteron, as compared to normal hadronic events, is the only difference observed between these two event samples. The rate $(N_{\bar{d}}/N_{\pi^-})/(N_{\bar{p}}/N_{\pi^-})^2$ measured in this experiment is of the same order of magnitude as the corresponding rate in soft hadron-hadron interactions.

It is a pleasure to thank E. Michel, W. Reinsch and Mrs. U. Djuanda for their competent technical help in running the experiment and analyzing the data. We thank Dr. H. Neemann, Dr. K. Wille and the DORIS group for the good operation of the storage ring. The visiting groups wish to thank the DESY directorate for the support and the kind hospitality extended to them.

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PRODUCTION AND DECAY OF THE CHARGED D^* MESON IN e^+e^- ANNIHILATION AT 10 GeV CENTRE-OF-MASS ENERGY

ARGUS Collaboration

H. ALBRECHT, U. BINDER, G. DREWS, G. HARDER, H. HASEMANN, A. PHILIPP,
W. SCHMIDT-PARZEFALL, H. SCHRÖDER, H.D. SCHULZ, F. SELONKE, R. WURTH
DESY, Hamburg, Germany

A. DRESCHER, B. GRÄWE, U. MATTHIESEN, H. SCHECK, J. SPENGLER, D. WEGENER
Institut für Physik, Universität Dortmund ¹, Germany

R. HELLER, K.R. SCHUBERT, J. STIEWE, R. WALDI, S. WESELER
Institut für Hochenergiephysik, Universität Heidelberg ¹, Germany

K.W. EDWARDS ², W.R. FRISKEN ³, Ch. FUKUNAGA ³, M. GODDARD ³, P.C.H. KIM ⁴,
R. KUTSCHKE ⁴, D.B. MacFARLANE ⁴, J.A. McKENNA ⁴, K. McLEAN ⁵, A. NILSSON ⁵, R.S. ORR ⁴,
P. PADLEY ⁴, P.M. PATEL ⁵, J.D. PRENTICE ⁴, H.C.J. SEYWERD ⁴, B.J. STACEY ⁴,
T.-S. YOON ⁴, J.C. YUN ²
Institute of Particle Physics ⁶, Canada

R. AMMAR, D. COPPAGE, R. DAVIS, S. KANEKAL, N. KWAK
University of Kansas ⁷, Lawrence, KS, USA

P. BÖCKMANN ⁸, L. JÖNSSON, Y. OKU
Institute of Physics, University of Lund ⁹, Sweden

M. DANILOV, V. LUBIMOV, V. MATVEEV, N. NAGOVITSIN, V. RYLTSOV, Yu. SEMENOV,
V. SHEVCHENKO, V. SOLOSHENKO, V. SOPOV, I. TICHOMIROV, Yu. ZAITSEV
Institute of Theoretical and Experimental Physics, Moscow, USSR

and

R. CHILDERS, C.W. DARDEN and H. GENNOW ¹⁰
University of South Carolina ¹¹, Columbia, SC, USA

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² Carleton University, Ottawa, Canada.

³ York University, Downsview, Canada.

⁴ University of Toronto, Toronto, Canada.

⁵ McGill University, Montreal, Canada.

⁶ Supported by the Natural Sciences and Engineering Research Council, Canada.

⁷ Supported by the US National Science Foundation and a University of Kansas Faculty Improvement award.

⁸ Present address: CERN, Geneva, Switzerland.

⁹ Supported by the Swedish Research Council.

¹⁰ On leave of absence from the University of Stockholm, Sweden.

¹¹ Supported by the US Department of Energy, under contract DE-AS09-80ER10690.

Using the ARGUS detector at DORIS we have observed the production of the charged D^* meson in e^+e^- annihilation at a center of mass energy of 10 GeV. The D^* fragmentation function has been measured using the decay channels $D^{*+} \rightarrow D^0\pi^+$ and $D^0 \rightarrow K^-\pi^+$ and $K^-\pi^+\pi^-$.

We find $\sigma \cdot \text{Br}$ for the channels $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow K^-\pi^+\pi^-$ to be $(23.6 \pm 2.2 \pm 4.7)$ pb and $(51.0 \pm 4.6 \pm 15.5)$ pb respectively, and the ratio of branching ratios $\text{Br}(D^0 \rightarrow K^-\pi^+\pi^-)/\text{Br}(D^0 \rightarrow K^-\pi^+)$ = $2.17 \pm 0.28 \pm 0.23$. In addition we measure the mass difference $M(D^{*+}) - M(D^0)$ to be $(145.46 \pm 0.07 \pm 0.03)$ MeV, and set an upper limit for $D^0 - D^0$ mixing of 0.11.

High energy, non-resonant e^+e^- annihilation into hadrons proceeds through the formation of a primary $q\bar{q}$ pair which fragments into two hadron jets. Fast charmed hadrons will, in general, contain primary c quarks since the production of $c\bar{c}$ pairs in the fragmentation process is expected to be highly suppressed. The fragmentation process for c quarks can thus be studied by measuring the production of fast charmed mesons [1].

In this letter we present measurements of D^{*+} production (in the following we will omit explicit reference to charge conjugate states) at the T and T' resonance energies. The fragmentation function is compared to other experimental results and to two theoretical models, the ratio of the decay widths, and the cross section times branching ratios, of $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow K^-\pi^+\pi^-$ are determined. We also present a determination of the D^{*+} , D^0 mass difference and an upper limit on $D^0 - D^0$ mixing.

The data discussed here were collected with the ARGUS detector at the DORIS II storage ring at DESY. The event sample consists of 40 events/pb; 23% on the T , 67% on the T' , and 10% on the continuum just below the T' .

The ARGUS detector is a solenoidal magnetic spectrometer having a field of 0.8 T. The main characteristics of the detector, and the triggering scheme used have been described elsewhere [2]. In the following analysis we have used only information from the drift chamber and from the time-of-flight counters.

The ARGUS drift chamber [3] is 2 m long and 0.9 m in radius. There are 5940 sense wires arranged in 36 concentric layers. Both drift time and the ionisation deposited are digitised. On average the spatial resolution is 170μ giving a momentum resolution of σ_p/p = 0.012 at 1 GeV/c.

In determining the specific ionization [dE/dx] of a track the truncated mean of the ionization deposited in a maximum of 36 chamber cells is used. This results

in a resolution of $\sigma(dE)/dE = 0.042$. Fig. 1a shows a scatter plot of momentum versus dE/dx for a random selection of tracks traversing at least 20 chamber cells. The bands corresponding to π , K, p are clearly separated. Better than three standard deviation separation is achieved for π and K below 700 MeV/c, and for K and p below 1200 MeV/c.

Surrounding the drift chamber there is a system of time-of-flight [TOF] counters [4]. There are 64 scintillators, each 2 cm thick, in the barrel system and 48 in each end cap. In the barrel system the scintillators have a photomultiplier at each end, while those in the end cap are equipped with only one photomultiplier. In addition to digitising the time on each photomultiplier, the pulse height is also digitised to allow for off-line correction of the timing. A time resolution of 220 ps is achieved in the barrel counters, and 230 ps in the end caps. Fig. 1b shows a scatter plot of momentum versus (mass)². The separation achieved is similar to that using the drift chamber.

For each track in an event a χ^2 for each mass hypothesis is calculated by adding the corresponding χ^2 values for the dE/dx and TOF measurements. The normalized probability for each mass hypothesis is then:

$$P_i = \exp(-\chi_i^2/2) / \sum \exp(-\chi_j^2/2), \quad i = \pi, K, p.$$

A track is considered a candidate for each mass hypothesis which gives an acceptable probability. Tracks giving an acceptable probability for more than one mass hypothesis enter into several mass combinations with equal weight. The effect of varying the probability cut in the range 0.01 to 0.03 was studied and the results of the analysis were found to be insensitive to the exact value chosen in this range.

We have identified charged D^* mesons by means of a well established procedure [5] which exploits the low Q value (5.8 MeV) of the decay $D^{*+} \rightarrow D^0\pi^+$. This gives very fine mass resolution in the mass differ-

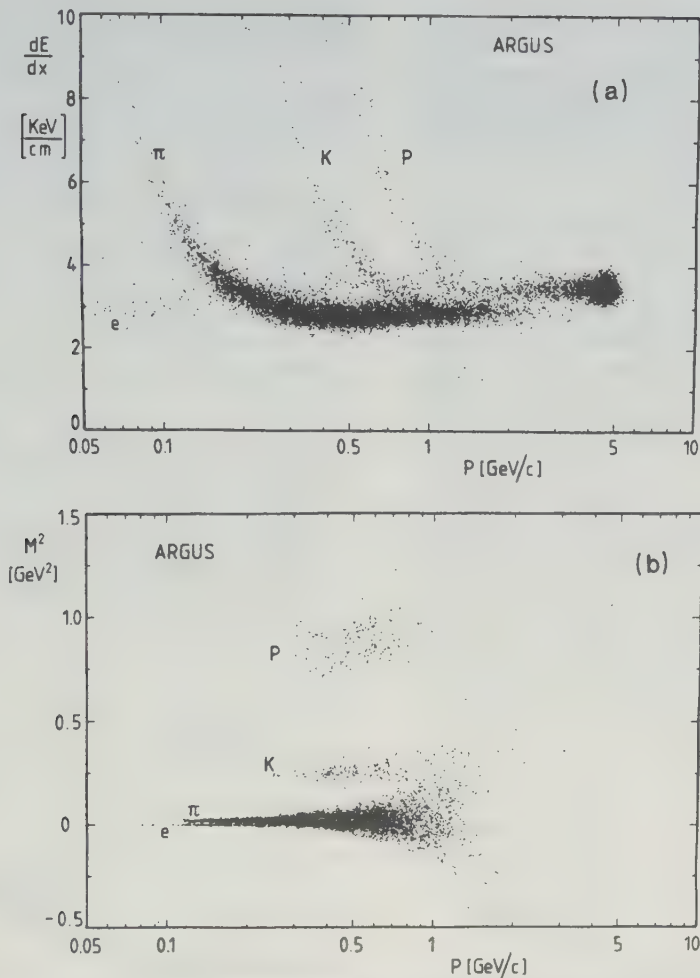


Fig. 1. (a) Scatter plot of dE/dx versus $\log(p)$ in the ARGUS drift chamber. The bands attributed to e , π , K , and p are indicated. (b) Scatter plot of $(\text{mass})^2$ versus $\log(p)$ obtained using the ARGUS TOF system. The bands for e , π , K , and p are indicated.

ence $\Delta M = M(D^0\pi^+) - M(D^0)$, and allows the cascade decay events to be seen in the presence of large combinatorial background. To search for the decays

$$D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+, \quad (1)$$

and

$$D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+ \pi^-, \quad (2)$$

we have formed all invariant mass combinations of K^- candidates with two and four charged π combinations of net charge +2. The mass hypothesis probability cut

was set ≥ 0.01 . This very loose probability cut reduces the background considerably while losing only a negligible amount of the signal.

In figs. 2a and 2c we show the mass difference distributions for $M(K^- \pi^+ \pi^+) - M(K^- \pi^+)$ and $M(K^- \pi^+ \pi^+ \pi^+) - M(K^- \pi^+ \pi^+ \pi^-)$. The subcombina-

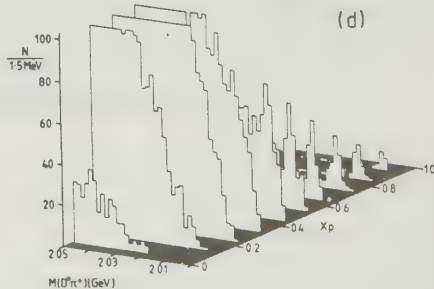
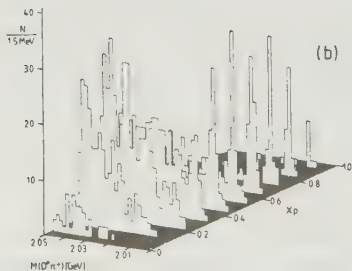
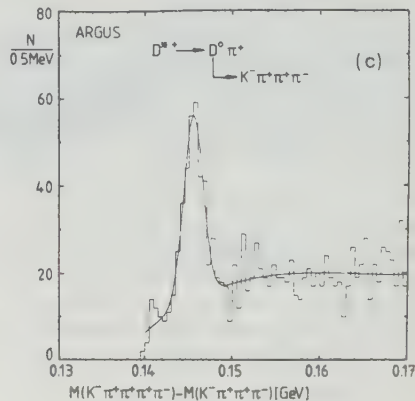
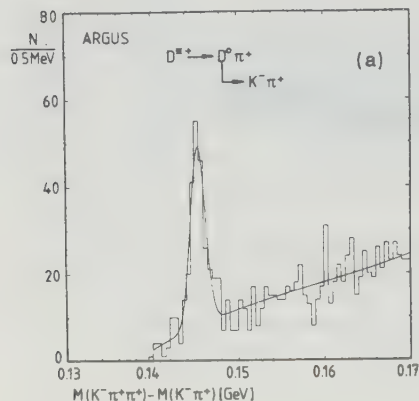


Fig. 2. (a) The mass difference distribution for channel (1). A mass selection, $1825 \leq M(K^- \pi^+) \leq 1905$ MeV was applied. D^{*+} production is evident. The solid line represents a gaussian fit with a polynomial background. The fit gives $\sigma = (0.87 \pm 0.12)$ MeV and $M(D^{*+}) - M(D^0) = (145.41 \pm 0.10)$ MeV. (b) The effective mass distribution of $(D^0 \pi^+)$ versus the fragmentation variable x_p for channel (1). The $K^- \pi^+$ combinations were constrained to the known D^0 mass in a kinematic fit. (c) As (a), but for channel (2). A mass selection of $1835 \leq M(K^- \pi^+ \pi^+ \pi^-) \leq 1895$ MeV and a cut of $x_E \geq 0.6$ were applied, where $x_E = 2E(D^*)/\sqrt{s}$. A fit gives $\sigma = (1.11 \pm 0.11)$ MeV and $M(D^{*+}) - M(D^0) = (145.51 \pm 0.11)$ MeV. (d) As (b), but for channel (2).

tions $K^- \pi^+$, in the former, and $K^- \pi^+ \pi^+ \pi^-$ in the latter, were required to be in the range of the D^0 mass, specifically $1825 \leq M(K^- \pi^+) \leq 1905$ MeV, and $1835 \leq M(K^- \pi^+ \pi^+ \pi^-) \leq 1895$ MeV.

In both distributions there is a clear signal for the cascade decay $D^{*+} \rightarrow D^0 \pi^+$. The fitted mass difference for channels (1) and (2) are 145.41 ± 0.10 and 145.51 ± 0.11 respectively. This yields an average of:

$$\Delta M = M(D^{*+}) - M(D^0) = (145.46 \pm 0.07 \pm 0.03) \text{ MeV.}$$

This is in good agreement with the world average [6] of (145.41 ± 0.24) MeV, and is considerably more precise. The estimated systematic error of 0.03 MeV includes the effect of the 0.2% uncertainty in the magnetic field calibration, of uncertainties in corrections for energy losses between vertex and drift chamber, and of varying the assumed form of the background shape.

The invariant mass distribution for $K^- \pi^+$ and $K^- \pi^+ \pi^+ \pi^-$ contain essentially the same information as that contained in the mass difference distributions shown in figs. 2a and 2c, and are not shown here. However, fitting these mass distributions with a gaussian line shape, plus a third order polynomial background confirms our overall mass scale and our knowledge of the experimental mass resolution. The fits yielded 191 ± 19 events at a fitted mass of (1864 ± 4) MeV in channel (1) and 216 ± 21 events at a fitted mass of (1866 ± 3) MeV in channel (2). The masses in both channels agree well with previously reported [6] values of the D^0 mass. The widths of the signals are in very good agreement with the Monte Carlo predictions of 30 MeV in channel (1) and 20 MeV in channel (2).

The fragmentation of a c quark into a charmed meson is expected to result in a hard momentum spectrum, while background invariant mass combinations should have a much softer momentum spectrum. In figs. 2(b) and 2(d) we show plots of the $D^0 \pi^+$ invariant mass spectrum against the fragmentation variable x_p , where $x_p = p_{D^0}/p_{\text{Max}}$ with $p_{\text{Max}} = (E_{\text{beam}}^2 - M_{D^0}^2)^{1/2}$. We note that both x_p and the energy scaling variable $x_E = E_{D^0}/E_{\text{beam}}$ have been used in the literature. These are approximations to the light-core variable $z = (E + p_{\parallel})_{\text{hadron}}/(E + p)_{\text{quark}}$, equivalent in the scaling limit [7]. The variable x_p used here has the additional virtue of spanning the same range [0, 1] for all experiments, regardless of the center of mass energy. The alternative choice, x_E , has a different thresh-

old for our result and for those from PETRA and PEP. In producing these invariant mass distributions the $K^- \pi^+$ and $K^- \pi^+ \pi^+ \pi^-$ combinations were constrained to the D^0 mass and a kinematic fit was performed. The number of D^{*+} events in each x_p bin was extracted by fitting a gaussian with width fixed to the Monte Carlo prediction of the mass resolution, plus a polynomial background, to the $D^0 \pi^+$ mass spectrum in each x_p bin.

Acceptances were calculated for both channels by means of a Monte Carlo simulation. Events were generated for the process $e^+ e^- \rightarrow c \bar{c}$ and allowed to fragment into D^{*+} according to the Field and Feynman model [8]. The resulting final state particles were tracked through a simulation of the ARGUS detector and analysed with the standard program chain. The calculated acceptances as a function of x_p range from 0.13 at x_p of 0.25 to 0.33 at x_p of 0.95 for channel (1). The corresponding range of acceptances for channel (2) is from 0.08 to 0.21.

We have estimated the systematic uncertainty in the acceptance calculation by comparing the geometrical acceptance for events of this kinematical configuration with the acceptance estimate from the full Monte Carlo simulation. This comparison results in an estimate of 0.78 for the single track efficiency. A sample of representative multihadron events was also scanned by physicists. For events within the cuts for this analysis the single track efficiency was estimated to be 0.82. This leads to a 16% systematic uncertainty on the acceptance for channel (1) and 28% for channel (2). However, in determining the ratio of the branching ratios of the two channels the uncertainty on the relative acceptances reduces to 10.5%.

After acceptance correction the relative branching ratio of the two channels is:

$$\text{Br}(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-) / \text{Br}(D^0 \rightarrow K^- \pi^+) =$$

$$= 2.17 \pm 0.28 \pm 0.23.$$

This is a significant improvement in precision compared to the previous world average of 1.92 ± 0.67 [6].

Above x_p of 0.5 the cross section times branching ratios ($\sigma \cdot \text{Br}$) for channels (1) and (2) are $(14.0 \pm 1.3 \pm 2.6)$ pb and $(30.3 \pm 2.7 \pm 9.0)$ pb respectively. The systematic errors include the acceptance uncertainty added in quadrature with an uncertainty on the lumi-

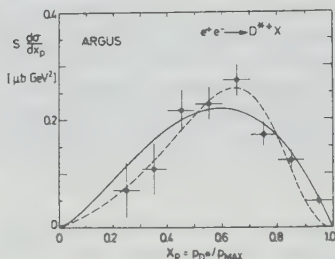


Fig. 3. $s \, d\sigma/dx_p$ for the D^{*+} based on the two channels. The error bars are statistical only. The dotted and solid curves result from fits of the expressions (3) and (4) respectively.

nosity measurement of 10%. The production rates of the D^{*+} on the T , T' , and the continuum are proportional to the luminosity divided by the square of the center of mass energy. Thus there is no indication, at the present level of statistics, of any D^{*+} production from the resonances.

From the number of D^{*+} events extracted as a function of x_p we have produced the D^{*+} fragmentation function, by combining the data in both channels. The result, corrected for acceptance, is shown in fig. 3. In determining the absolute normalization of this distribution we have used the values of ref. [6] for the branching ratios of $D^{*+} \rightarrow D^0 \pi^+$ and $D^0 \rightarrow K^- \pi^+$, combined with the above value for the ratio of branching ratios. It is interesting to compare this measured distribution to forms predicted theoretically. We have compared the data to two typical models, that of Peterson et al. [9] where

$$s \, d\sigma/dx_p \sim x_p^{-1} [1 - 1/x_p - \epsilon/(1 - x_p)]^{-2}, \quad (3)$$

and that of Kartvelishvili et al. [10] where:

$$s \, d\sigma/dx_p \sim x_p^\alpha (1 - x_p). \quad (4)$$

No attempt has been made to correct these expressions for the effects of photon or gluon radiation.

The fits for forms (3) and (4) are shown as the dotted and full curves in fig. 3. The best fitted parameters are $\epsilon = 0.19 \pm 0.03$ with $\chi^2 = 19.2$ for 6 degrees of freedom, and $\alpha = 1.5 \pm 0.2$ with $\chi^2 = 7.4$ also for 6 degrees of freedom. Our data favour the form (4). They are less consistent with the form in (3), the main disagreement is in the x_p bin from 0.9 to 1.0. A

change of variable from x_p to $x_E = 2E(D^*)/\sqrt{s}$ or the inclusion of radiative corrections does not change this conclusion.

The measurement of the D^* fragmentation function presented here represents an improvement in statistical precision over results from CLEO in a similar energy range and from PETRA and PEP at higher energies [1]. Within the statistical uncertainties our measurement is in agreement with these results. Comparison of published measurements can be found in the literature [7].

Using the fitted form of the fragmentation function due to Kartvelishvili we have evaluated σ_{Br} for channels (1) and (2) extrapolated to $x_p = 0$. The results are respectively $(23.6 \pm 2.2 \pm 4.7)$ pb and $(51.0 \pm 4.6 \pm 15.5)$ pb.

We have looked for the effect of $D^0 - \bar{D}^0$ mixing in our data. A summary of previous upper limits was given in a recent publication [11]. The method used here is based on the search for wrong signed D^0 decay of the D^{*+} in channel (1), that is the presence of D^{*+} -like events in the mass combination $K^+ \pi^- \pi^+$. Since the main source of background is particle misidentification in the correct sign decays, we have chosen to work with a highly restricted sample. The only changes from the above selection criteria were to increase the probability cut from 0.01 to 0.10 and to require $x_E \geq 0.7$. The two mass difference plots obtained are shown in fig. 4. There are 30 events in the

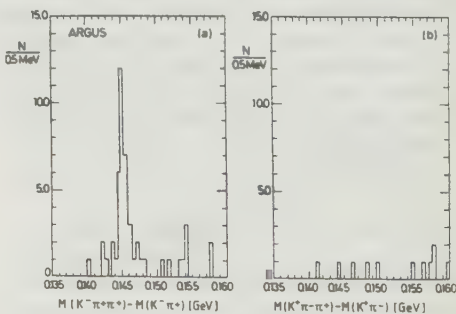


Fig. 4. (a) The distribution of ΔM for the correct charge combinations $M(K^- \pi^+ \pi^+) - M(K^- \pi^+)$. (b) The distribution of ΔM for the wrong charge combinations $M(K^+ \pi^- \pi^+) - M(K^+ \pi^-)$.

correct sign mode, and 2 events in the wrong sign mode, where 2 background events were expected. This observation yields an 11% upper limit for $D^0 - \bar{D}^0$ mixing at 90% confidence level.

In summary, we have determined more precise values for the mass difference of the D^{*+} and D^0 and for the relative branching ratio of D^0 into $K^-\pi^+$ and $K^-\pi^+\pi^+\pi^-$ than previously known. The $D^0 - \bar{D}^0$ mixing is found to be smaller than 11%. Finally, the fragmentation function of the D^{*+} meson is in very good agreement with the form $x^\alpha (1-x)$, while its agreement with the widely used Peterson form is less good.

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PRODUCTION AND DECAY OF THE F MESON IN e^+e^- ANNIHILATION AT 10 GeV CENTRE-OF-MASS ENERGY

The ARGUS Collaboration

H. ALBRECHT, U. BINDER, G. DREWS, G. HARDER, H. HASEMANN, A. PHILIPP,
W. SCHMIDT-PARZEFALL, H. SCHRÖDER, H.D. SCHULZ, F. SELONKE, R. WURTH
DESY, Hamburg, Fed. Rep. Germany

A. DRESCHER, B. GRÄWE, W. HOFMANN¹, A. MARKEES², U. MATTHIESEN,
H. SCHECK, J. SPENGLER, D. WEGENER

Institut für Physik, Universität Dortmund³, Dortmund, Fed. Rep. Germany

R. HELLER⁴, K.R. SCHUBERT, J. STIEWE, R. WALDI, S. WESELER

Institut für Hochenergiephysik, Universität Heidelberg⁵, Heidelberg, Fed. Rep. Germany

N.N. BROWN⁵, K.W. EDWARDS⁶, W.R. FRISKEN⁷, Ch. FUKUNAGA⁷, D.J. GILKINSON⁸,
D.M. GINGRICH⁸, M. GODDARD⁷, P.C.H. KIM⁸, R. KUTSCHKE⁸, D.B. MACFARLANE⁸,
J.A. McKENNA⁸, K.W. McLEAN⁵, A.W. NILSSON⁵, R.S. ORR⁸, P. PADLEY⁸, P.M. PATEL⁵,
J.D. PRENTICE⁸, H.C.J. SEYWERD⁸, B.J. STACEY⁸, T.-S. YOON⁸, J.C. YUN⁶

Institute of Particle Physics⁹, Canada

R. AMMAR, D. COPPAGE, R. DAVIS, S. KANEKAL, N. KWAK

University of Kansas¹⁰, Lawrence, KS, USA

P. BÖCKMANN¹¹, L. JÖNSSON, Y. OKU

Institute of Physics, University of Lund¹², Lund, Sweden

M. DANILOV, V. LUBIMOV, V. MATVEEV, N. NAGOVITSIN, V. RYLTSOV, A. SEMENOV,
Yu. SEMENOV, V. SHEVCHENKO, V. SOLOSHENKO, V. SOPOV, I. TICHOMIROV,
Yu. ZAITSEV

Institute of Theoretical and Experimental Physics, Moscow, USSR

R. CHILDERS, C.W. DARDEN and H. GENNOW¹³

University of South Carolina¹⁴, Columbia, SC, USA

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Using the ARGUS detector at DORIS, we have observed the production of $F^\pm$ mesons in e^+e^- annihilation at a centre of mass energy of 10 GeV through their subsequent decays into $\phi\pi^\pm$ and $\phi\pi^+\pi^-\pi^\pm$. The values obtained for $[R(e^+e^- \rightarrow FX) \cdot \text{Branching Ratio}]$ are $(1.47 \pm 0.32 \pm 0.20)\%$ and $(1.63 \pm 0.42 \pm 0.41)\%$ respectively. The observed mass is $(1973.6 \pm 2.6 \pm 3.0)\text{MeV}/c^2$. The F momentum spectrum is as expected for the fragmentation of c quarks into charmed mesons, but is somewhat softer than for fragmentation into D^* mesons. The relevant angular distributions are consistent with a spin-zero assignment of the F meson.

- ¹ Present address: University of California, Berkeley, CA, USA.
² Present address: Swiss Administration, Berne, Switzerland.
³ Supported by the Bundesministerium für Forschung und Technologie, Fed. Rep. Germany.
⁴ Present address: DESY, Hamburg, Fed. Rep. Germany.
⁵ McGill University, Montreal, Canada.
⁶ Carleton University, Ottawa, Canada.
⁷ York University, Downsview, Canada.
⁸ University of Toronto, Toronto, Canada.

- ⁹ Supported by the National Sciences and Engineering Research Council, Canada.
¹⁰ Supported by the US National Science Foundation and a University of Kansas Faculty Improvement award.
¹¹ Present address: CERN, Geneva, Switzerland.
¹² Supported by the Swedish Research Council.
¹³ On leave of absence from the University of Stockholm, Stockholm, Sweden.
¹⁴ Supported by the US Department of Energy, under contract DE-AS09-80ER10690.

We report here evidence for the production of F^* mesons in e^+e^- annihilation at $\sqrt{s} = 10$ GeV, and their decay into two channels. The data provide information both on the fragmentation of c quarks into $c\bar{s}$ states and on F decay branching ratios. Since understanding of heavy quark hadronisation is limited, it is interesting to compare the F fragmentation function with those already measured in D and D^* production. Measurement of the branching ratios of weak F decays gives insight into the interplay of the various possible decay mechanisms. Although the spectator model for heavy quark decay [1] describes the broad features of these decays, its shortcomings have already been demonstrated by results on the D^0 , D^+ lifetimes and also by the observation of F decay final states containing neither an s nor an $\bar{s}$ quark [2,3]. Studies of F production and decay will contribute considerably to the resolution of these questions.

Early experimental searches [2,4] for the F meson showed an enhancement of mass $2020 \text{ MeV}/c^2$ in channels containing η , η' and ϕ , all of which are expected in the quark decay (spectator) model. In 1983, CLEO [5] reported a state at $1970 \text{ MeV}/c^2$ decaying to $\phi\pi$, and presented strong evidence that it is indeed the F meson. Two subsequent experiments [6] have corroborated this discovery. The ARGUS collaboration has reported [7] the observation of the spin-1 excited state of the F , the F^* , which decays into $F\gamma$, where the F is seen in the $\phi\pi$ channel. We now report a detailed study of F production and decay both in the $\phi\pi$ channel and, for the first time, in the $\phi\pi^+\pi^-\pi^+$ channel.

The data presented here were collected using the ARGUS spectrometer at the DORIS II e^+e^- storage ring at DESY. The centre of mass energy range was from 9.4 to $10.6 \text{ GeV}/c^2$. A short description of the detector and its trigger may be found in ref. [8], and

its particle identification capabilities are described in ref. [9]. Data from a 62.7 pb^{-1} sample, comprising 8.6 pb^{-1} on the $T(9460)$ resonance, 38.2 pb^{-1} on the $T(10023)$, 11.1 pb^{-1} on the $T(10573)$, and 4.8 pb^{-1} on the continuum, were used for this analysis.

Events corresponding to e^+e^- annihilation into a multihadron final state were selected, as in ref. [8], by requiring ≥ 4 tracks reconstructed in the drift chamber and associated with the primary interaction point. Only tracks having $|\cos\theta| \leq 0.9$ and $p_T \geq 60 \text{ MeV}/c$ have been used in order to give a well defined acceptance and well measured tracks. In searching for the F signal, particle identification is essential. We have used both the specific ionisation measurements in the drift chamber (dE/dx) and time-of-flight (TOF) information for particle identification. A more detailed description is given in ref. [9]. Briefly, for each track in an event, the probability for each mass hypothesis is:

$$P_i = f_i e^{-x_i^2/2} / \sum_j f_j e^{-x_j^2/2},$$

$$i, j = \pi, K, p, \quad f_\pi = 5, \quad f_K, f_p = 1, \quad (1)$$

where the f_i are relative production abundances. In forming effective mass combinations, a track was used for all mass hypotheses for which this particle identification probability was greater than 5%. Almost all tracks with momenta below $700 \text{ MeV}/c$ are uniquely identified. As the momentum increases beyond $700 \text{ MeV}/c$, the proportion of ambiguous tracks increases steadily.

The invariant mass distribution of all K^+K^- pairs is shown in fig. 1. A clear ϕ signal is evident. A fitted Breit-Wigner resonance plus 3rd order polynomial background gives a mass of $(1019.7 \pm 0.1 \pm 0.1) \text{ MeV}/c^2$, a full width of $(8.1 \pm 0.4) \text{ MeV}/c^2$ and

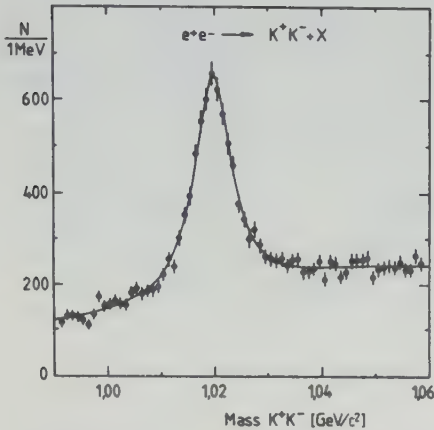


Fig. 1. K^+K^- invariant mass distribution in $e^+e^- \rightarrow K^+K^-X$.

(5079 ± 276) events above background within ± 15 MeV/c^2 of the ϕ mass. The mass and width (including detector resolution) are in good agreement with the accepted values [10].

To search for the decay modes $F^\pm \rightarrow \phi\pi^\pm$ and $F^\pm \rightarrow \phi\pi^+\pi^-\pi^\pm$, all combinations of K^+K^- candidates with invariant mass within ± 15 MeV/c^2 of the ϕ mass, and with $\chi^2 \leq 16$ for the mass hypothesis, were taken as ϕ candidates. Each ϕ was then combined with all $\pi^\pm$ and $(3\pi)^\pm$ candidates in the event. The following Monte Carlo motivated cuts were also applied:

$$p_{\phi\pi} \geq 1.5 \text{ GeV}/c, \quad -1.0 \leq \cos\theta_\phi \leq 0.8,$$

for all $\phi\pi$ combinations,

$$p_{\phi 3\pi} \geq 2.2 \text{ GeV}/c, \quad \text{for all } \phi 3\pi \text{ combinations},$$

where θ_ϕ is the angle, with respect to the F boost direction, of the ϕ in the F rest frame.

The resulting invariant mass distributions for the $\phi\pi$ and $\phi 3\pi$ are shown in figs. 2a and 2b, respectively. Both distributions show enhancements near 1970 MeV/c^2 . A gaussian of fixed width plus a 3rd order polynomial background was fitted to each distribution. Table 1 shows the resulting numbers of fitted events. Combining the two channels as independent

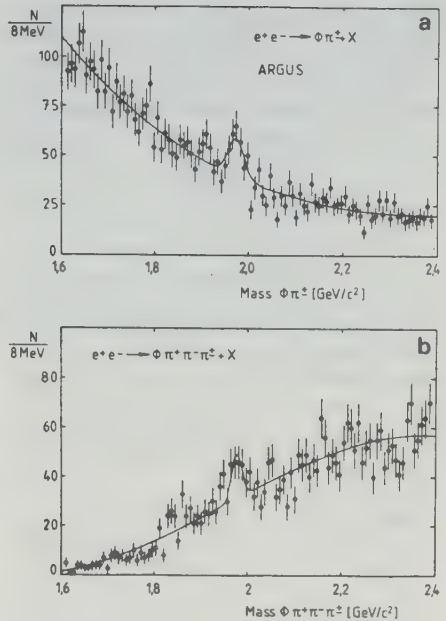


Fig. 2. (a) $K^+K^-\pi^+$ invariant mass distribution with mass (K^+K^-) in the ϕ region, and $p_{KK\pi} \geq 1.5$ GeV/c and $-1.0 \leq \cos\theta_\phi \leq 0.8$. (b) $K^+K^-\pi^+\pi^-\pi^+$ invariant mass distribution with mass (K^+K^-) in the ϕ region, and $p_{KK3\pi} \geq 2.2$ GeV/c .

observations, the total statistical significance of the signal is 6.3 standard deviations.

The values of the fixed widths for these fits were obtained from Monte Carlo studies: $\sigma = 16.8$ MeV/c^2 for $\phi\pi$, and $\sigma = 11.2$ MeV/c^2 for the $\phi 3\pi$ channel. In the ARGUS Monte Carlo, events are generated for the process $e^+e^- \rightarrow c\bar{c}$ and then fragmented according to the Field and Feynman model [11]. The resulting particles are tracked through a simulation of the ARGUS detector and events are then reconstructed and analysed with the standard programs.

The fitted masses in the two channels are consistent. The mean mass is $(1973.6 \pm 2.6 \pm 3.0)$ MeV/c^2 , weighting by the inverse square of the error on mass in each channel. The systematic error is primarily due

Table 1
Fitted results for $F^\pm$ decay channels.

	$\phi\pi^\pm$	$\phi\pi^+\pi^-\pi^\pm$
uncorrected number of events	100.1 $^{+22.1}_{-21.4}$	62.4 $^{+16.2}_{-15.5}$
significance (σ)	4.7	4.0
mass (MeV/ c^2)	1972.8 $\pm 3.1 \pm 3.0$	1975.7 $\pm 4.7 \pm 3.0$
total acceptance (%) ^{a)}	12.8	7.2
$\sigma_F \cdot BR$ (pb) ^{b,c)}	12.7 $\pm 2.8 \pm 1.7$	14.1 $\pm 3.6 \pm 3.5$
$R_F \cdot BR$ (%) ^{c,d)}	1.47 $\pm 0.32 \pm 0.20$	1.63 $\pm 0.42 \pm 0.41$
sideband ϕ control sample		
uncorrected number of events	16.9 ± 19.5	-1.8 ± 13.7

a) A factor of 0.49 has been included for the unseen ϕ decay channels.

b) σ_F = inclusive cross section for $e^+e^- \rightarrow F^\pm X$.

c) BR = branching ratio of F decay mode.

d) $R_F = \sigma_F/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$.

to the uncertainty in the magnetic field calibration. The mass agrees well with previously reported results in the $\phi\pi$ channel [5,6].

No signal is seen above background in the $KK\pi$ ($KK3\pi$) mass distribution when the analysis is repeated with K^+K^- invariant mass in a 52 MeV/ c^2 (30 MeV/ c^2) sideband outside the ϕ mass band, as shown in figs. 3a and 3b. In searching for a signal in the sideband distributions, we fitted gaussians of width equal to the Monte Carlo predictions and mass equal to that found for the signals within the ϕ band. The fitted numbers of events for the sideband ϕ signals are shown in table 1

In addition, we have checked that the angular distributions of $F \rightarrow \phi\pi$ and $F \rightarrow \phi3\pi$ are consistent with the $J^P = 0^-$ assignment of the F meson.

The angular distribution of the ϕ (with respect to the F boost direction) in the F rest frame is isotropic, as expected, since the F has spin zero. The angular distribution was obtained by dividing the invariant mass distribution of each channel into five bins of $\cos\theta_\phi$, and extracting the F signal in each bin. Acceptance corrections were then applied, the results were normalized, and both channels were combined using weighted means. The resulting distribution is shown (solid points) along with the background distribution (open squares), and the expected isotropic distribution (solid line), in fig. 4a.

In the $F \rightarrow \phi\pi$ decay, the angular distribution of the K^+ in the ϕ rest frame (with respect to the π)

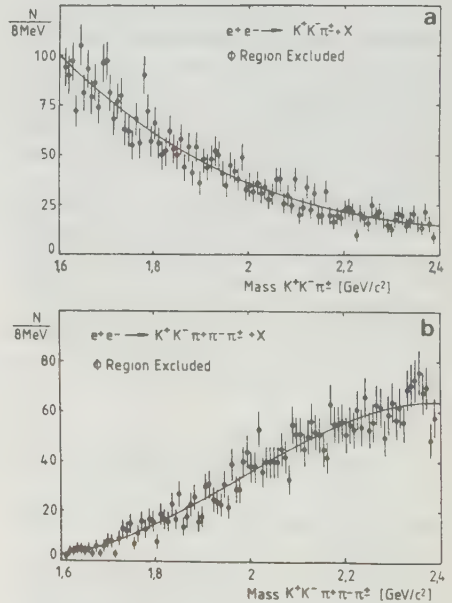
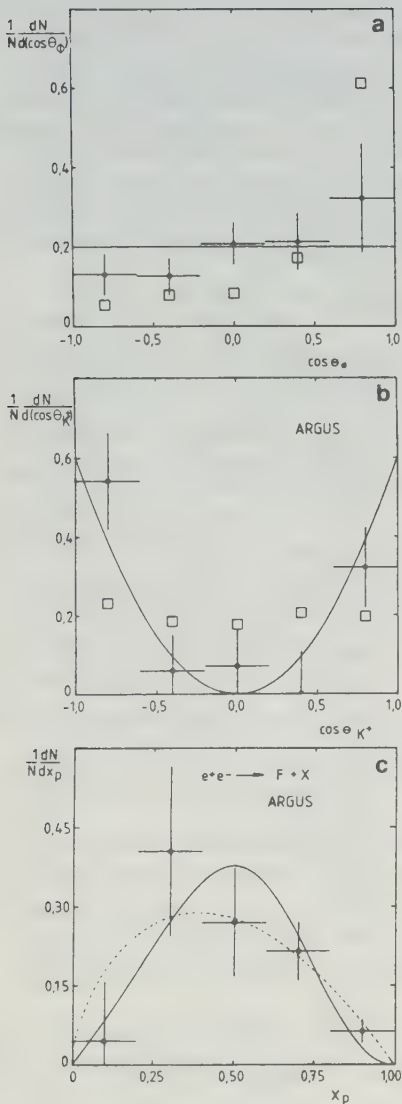


Fig. 3. (a) $K^+K^-\pi^+$ invariant mass distribution with mass (K^+K^-) outside the ϕ region with cuts $p_{KK\pi} > 1.5$ GeV/ c and $-1.0 < \cos\theta_\phi < 0.8$. (b) $K^+K^-\pi^+\pi^-$ invariant mass distribution with mass (K^+K^-) outside the ϕ region and with a cut on $p_{KK3\pi} > 2.2$ GeV/ c .



should be of the form $\cos^2\theta_K$, since the ϕ must have zero helicity in the F rest frame. The signal was extracted as in the ϕ angular distribution, acceptance corrected and normalized, and is shown in fig. 4b (solid points) along with the background distribution (open squares), and the expected $\cos^2\theta_K$ distribution (solid curve).

The background angular distributions were obtained by taking the number of entries under the peak in each angular bin in a region 72 MeV/ c^2 wide for the $\phi\pi$, and 56 MeV/ c^2 wide for the $\phi 3\pi$. The acceptance corrections were then applied, and the resulting distributions were normalized. The angular distributions of the background differ from those of the signal.

It is expected [12] that a charmed meson resulting from c quark fragmentation will have a hard momentum spectrum. We have measured the momentum spectrum of the F by dividing the invariant mass distributions into five bins of x_p , where

$$x_p = p_F/p_{\max}, \quad p_{\max} = (E_{\text{beam}}^2 - M_F^2)^{1/2}, \quad (2)$$

and extracting the F signal in each bin. The results in the two channels were corrected for the momentum dependent acceptance and combined using weighted means to give the final result in fig. 4c. The x_p distribution is hard and conforms to the expectation for heavy quark production. Peterson et al. [13] suggest a fragmentation function of the form:

$$\frac{dN}{dx_p} \sim x_p^{-1} \left(1 - \frac{1}{x_p} - \frac{\epsilon}{1-x_p} \right)^{-2}, \quad (3)$$

while Kartvelishvili et al. [14] propose:

$$\frac{dN}{dx_p} \sim x_p^\alpha (1-x_p). \quad (4)$$

Fig. 4. (a) Acceptance corrected angular distribution of the ϕ in the F rest frame (with respect to the F boost direction) for the combined $\phi\pi$ and $\phi 3\pi$ channels (solid points). The corresponding background distribution is also shown (open squares). The solid line is the expected isotropic distribution. (b) Acceptance corrected angular distribution of the K^+ in the ϕ rest frame (with respect to the π direction) for the $\phi\pi$ (solid points). The corresponding background distribution is also shown (open squares). The solid curve is the expected $\cos^2\theta_K$ distribution. (c) Acceptance corrected fragmentation function of the F meson in $e^+e^- \rightarrow FX$ for the two channels $F \rightarrow \phi\pi$ and $F \rightarrow \phi 3\pi$ combined, where $x_p = p_F/p_{\max}$. The solid curve is a fit to the function of Peterson et al. [13], the dashed curve is a fit to that of Kartvelishvili et al. [14].

Fitting these forms to the measured distribution yields $\epsilon = 0.50^{+0.22}_{-0.14}$ with $\chi^2 = 2.9$ for three degrees of freedom (solid curve) and $\alpha = 0.64^{+0.22}_{-0.20}$ with $\chi^2 = 2.3$ for three degrees of freedom (dashed curve), respectively, shown in fig. 4c. The F fragmentation function measured here is softer than that of the D^* [9]. This softening is partly explained by the ratio of the masses of the s and u or d quarks accompanying the c quark in the F and D^* mesons respectively. Some slight softening of the fragmentation function is a consequence of the fact that a large proportion of the observed F's are due to the cascade decay, $F^* \rightarrow F\gamma$ [7].

The F production cross section times the branching ratio for each channel ($\sigma_F \cdot BR$), and the production cross section times branching ratio relative to μ pair production ($R_F \cdot BR$) are shown in table 1. These values are acceptance corrected and extrapolated to cover the entire x_p range using eq. (3) with the fitted value of $\epsilon = 0.50$. The systematic error in the $\phi 3\pi$ channel is increased due to the uncertainty in the F width in this channel. If the signals are fitted with free widths, the $\phi\pi$ width is consistent with Monte Carlo studies, but the $\phi 3\pi$ width is larger than the Monte Carlo width and has a large uncertainty. Our value for ($R_F \cdot BR$) in the $\phi\pi$ channel is in good agreement with the CLEO result [5] (2.0 ± 0.5)%, obtained at the same e^+e^- energy, but it is somewhat smaller than the TASSO result [6] ($6.4 \pm 1.3 \pm 1.9$)%, obtained at a higher energy.

The ratio

$$\frac{BR(F^{\pm} \rightarrow \phi\pi^+\pi^-\pi^{\pm})}{BR(F^{\pm} \rightarrow \phi\pi^{\pm})} = 1.11 \pm 0.37 \pm 0.28, \quad (5)$$

is smaller than the ratio for the analogous D^0 decays [9]:

$$\frac{BR(D^0 \rightarrow K^-\pi^+\pi^+\pi^-)}{BR(D^0 \rightarrow K^-\pi^+)} = 2.17 \pm 0.35. \quad (6)$$

A smaller ratio is expected for the F decays due to phase space considerations.

To conclude, we have observed the decay $F^{\pm} \rightarrow \phi\pi^+\pi^-\pi^{\pm}$ and confirmed the observation of $F^{\pm} \rightarrow \phi\pi^{\pm}$. The average mass of the F is found to be $(1973.6 \pm 2.6 \pm 3.0) \text{ MeV}/c^2$. The branching ratio of $F^{\pm} \rightarrow \phi(3\pi)^{\pm}$ is $(1.11 \pm 0.37 \pm 0.28)$ times that of $F^{\pm} \rightarrow \phi\pi^{\pm}$. The angular distributions of the ϕ (in both channels)

and the K^+ (in the $\phi\pi$ channel) are consistent with a spin zero assignment of the F. Finally, the fragmentation function of the F is found to be of the general form expected for heavy quark fragmentation.

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EVIDENCE FOR F^* MESON PRODUCTION IN e^+e^- ANNIHILATION AT 10 GeV CENTER-OF-MASS ENERGY

ARGUS Collaboration

H. ALBRECHT, G. DREWS, G. HARDER, H. HASEMANN, A. PHILIPP, W. SCHMIDT-PARZEFALL,
H. SCHRÖDER, H.D. SCHULZ, F. SELONKE, R. WURTH
DESY, Hamburg, Germany

A. DRESCHER, B. GRÄWE, U. MATTHIESEN, H. SCHECK, J. SPENGLER, D. WEGENER
Institut für Physik, Universität Dortmund, Germany

R. HELLER, K.R. SCHUBERT, J. STIEWE, R. WALDI, S. WESELER
Institut für Hochenergiephysik, Universität Heidelberg, Germany

K. EDWARDS¹, W.R. FRISKEN⁴, Ch. FUKUNAGA⁴, M. GODDARD⁴, P.C.H. KIM³,
R. KUTSCHKE³, D.B. MacFARLANE³, J.A. McKENNA³, K. McLEAN², A. NILSSON², R.S. ORR³,
P. PADLEY³, P.M. PATEL², J.D. PRENTICE³, H.C.J. SEYWERD³, B.J. STACEY³, T.-S. YOON³,
J.C. YUN¹
Institute of Particle Physics, Canada

R. AMMAR, D. COPPAGE, R. DAVIS, S. KANEKAL, N. KWAK
University of Kansas, Lawrence, KA, USA

P. BÖCKMANN⁵, L. JÖNSSON, Y. OKU
Institute of Physics, University of Lund, Sweden

M. DANILOV, V. LUBIMOV, V. MATVEEV, V. NAGOVITSIN, Yu. SEMENOV, V. SHEVCHENCO,
V. SOLOSHENKO, V. SOPOV, V. RYLTSOV, I. TICHOMIROV, Yu. ZAITSEV
Institute of Theoretical and Experimental Physics, Moscow, USSR

and

R. CHILDERS, C.W. DARDEN and H. GENNOW⁶
University of South Carolina, Columbia, SC, USA

Received 19 June 1984

Using the ARGUS detector at DORIS we have obtained evidence for a resonance which decays into an F meson and a photon. The observed mass is $2109 \pm 9 \pm 7$ MeV, which is $144 \pm 9 \pm 7$ MeV greater than the F meson mass. Its properties are consistent with those of the F^* meson with $J^P = 1^-$.

¹ Carleton University, Ottawa, Canada.

² McGill University, Montreal, Canada.

³ University of Toronto, Toronto, Canada.

⁴ York University, Downsview, Canada.

⁵ Present address: CERN, Geneva, Switzerland.

⁶ On leave of absence from University of Stockholm, Sweden.

In analogy with the D^* meson an excited F meson, the $J^P = 1^-, I = 0$ F^* meson is predicted by the quark model [1]. Unlike the D^* meson the F^* is forbidden by isospin conservation to decay strongly into $\pi^0 F$. This leaves the radiative decay as the dominant mode. Searches for the F^* meson have been made previously [2].

In this letter we report evidence for a stat of mass 2109 MeV decaying into an F^* meson and a photon, where the F^* meson is identified by its decay into $\Phi\pi^\pm$ [3,4]. From its production and decay properties we interpret this state to be the F^* meson.

The data presented here have been collected using the ARGUS detector at the DORIS II e^+e^- storage ring at DESY. The CM energy range was from 9.4 to 10.6 GeV. A short description of the detector and its trigger has been given in ref. [5], and its particle identification capabilities are described in ref. [6]. The event sample used for this analysis consists of 43.7 events/pb, comprising 8.7/pb on the $\Upsilon(1S)$ resonance, 25.1/pb on the $\Upsilon(2S)$, 5.4/pb on the $\Upsilon(4S)$ and 4.5/pb in the continuum.

Events corresponding to e^+e^- annihilation into multihadron final states were selected, as in ref. [5], by requiring that ≥ 4 tracks be reconstructed in the drift chamber and that they be associated with the primary interaction point. For charged particle identification we have used both the specific ionisation in the drift chamber (dE/dx) and the time-of-flight (TOF) information. For each track in an event the probability for each mass hypothesis is

$$P_i[\chi^2(dE/dx)_i + \chi^2(\text{TOF})_i], \quad i = \pi, K, p.$$

In forming effective mass combinations a track is entered with unity weight for each mass hypothesis for which the particle identification gives a probability larger than 3%. Almost all tracks having momenta below 700 MeV/c are uniquely identified. As the momentum increases beyond 700 MeV/c the proportion of ambiguous tracks also increases steadily.

For the photon detection we use the 1760 lead-scintillator-sandwich counters which have an energy resolution of $\sigma/E = (0.07^2 + 0.08^2 \text{ GeV}/E)^{1/2}$. All counters have been calibrated using Bhabba events and are systematically monitored with a laser-pulse system. To illustrate the photon reconstruction we show in fig. 1 the background-subtracted π^0 mass distribution. Fitting a gaussian gives a mass value

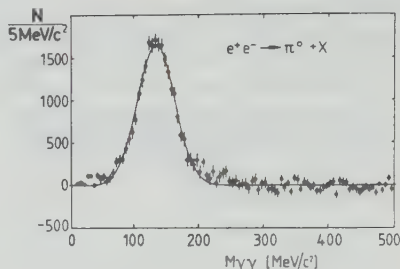


Fig. 1. The background-subtracted $\gamma\gamma$ mass distribution. The curve is a gaussian fit to the data.

$136.0 \pm 0.6 \pm 5$ MeV and a width of 26 ± 1 MeV, in agreement with an expected width of 24 MeV.

F meson candidates were obtained by forming all combinations of $K^+K^-\pi^\pm$ in the selected multihadronic events with the restriction that the invariant mass of the K^+K^- pair be in the range 1.014–1.025 GeV. In addition the momentum of the pion was required to be larger than 0.3 GeV as in our study of the F meson [4]. All such candidates were subsequently paired with all possible photons but under the restriction that the photon laboratory energy E_γ be larger than 110 MeV and that the momentum of the $\Phi\pi\gamma$ -system be larger than 1.8 GeV/c.

For the accepted $\Phi\pi\gamma$ -combinations we show in figs. 2a–2c the $\Phi\pi$ invariant mass distribution for three intervals in $M(\Phi\pi\gamma)$. There is a clear F signal correlated with a γ from the F^* interval with $M(\Phi\pi\gamma) = 2.08$ to 2.17 GeV while for the side bands there is little signal above background. Further evidence comes from a comparison of figs. 3a and 3b. Here the momentum of the $\Phi\pi$ system is selected to be larger than 1.65 GeV/c. In fig. 3a no extra photon was required, whereas in fig. 3b a photon from the F^* interval was asked for. Obviously this requirement leads to a substantial improvement of the F signal to background ratio. To show that the observed enhancement is due to F^* production and not artificially caused by a steeply falling photon spectrum and the E_γ cut chosen, we display in fig. 4 the invariant mass of the $\Phi\pi\gamma$ system as a function of the E_γ cut. Here we have required the $\Phi\pi$ system to be in a 20 MeV wide band around the F peak. As can be seen from fig. 4 there is a signal for all E_γ cuts between

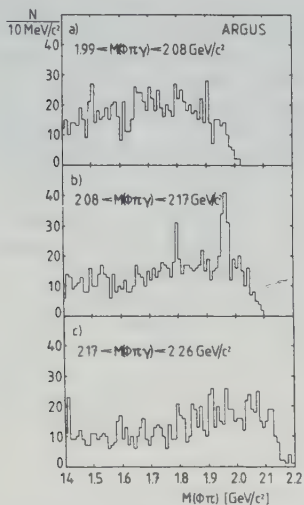


Fig. 2. (a)–(c) The invariant mass $M(\Phi\pi)$ for various intervals of the invariant mass $M(\Phi\pi\gamma)$. The momentum $P(\Phi\pi\gamma)$ of the $\Phi\pi\gamma$ system is required to be larger than 1.8 GeV/c.

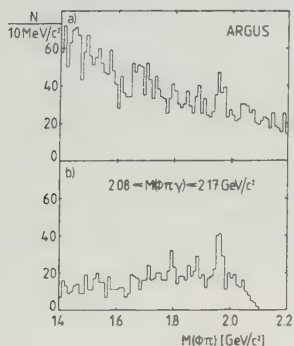


Fig. 3. (a) the number of $\Phi\pi$ combinations as a function of the invariant mass $M(\Phi\pi)$ without any requirement of an extra photon, but with the restriction $P(\Phi\pi) > 1.65$ GeV/c. (b) as (a) but requiring the invariant mass $M(\Phi\pi\gamma)$ to be in the F^* peak region.

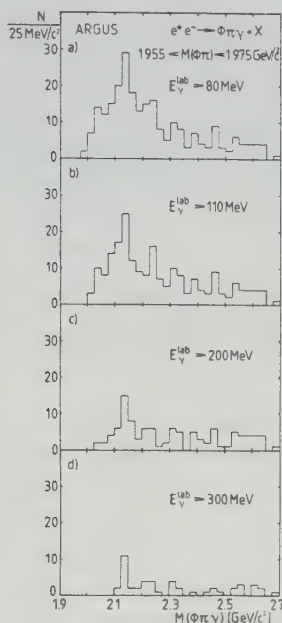


Fig. 4. The invariant mass $M(\Phi\pi\gamma)$ distributions as a function of the photon energy cut off. The mass of the $\Phi\pi$ system is required to be in a 20 MeV wide band around the F^* -peak.

80 and 300 MeV at the same $\Phi\pi\gamma$ mass of about 2.1 GeV.

The enhancement of the F signal in fig. 2b and the lack of it in the sidebands (figs. 2a,2c) as well as the observed reduction of the signal in fig. 4 with the increasing E_γ cut agrees well with a Monte Carlo simulation of F^* production. The simulation uses events generated according to the Field–Feynman model [7] where the fragmentation of the charmed quarks is adjusted to reproduce the fragmentation functions for D and F mesons in refs. [6,4]. The events are processed through a detector simulation program and subsequently reconstructed with our data analysis program. In addition we have undertaken a number of studies in order to exclude the possibility that the peak in fig. 2 is an artefact. We have used various event mixing methods, the method of cutting outside the Φ and F peaks, as well as Monte Carlo simulations

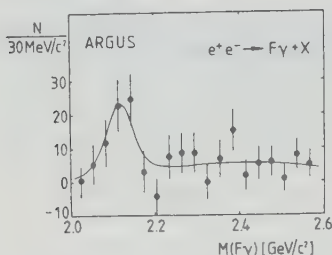


Fig. 5. The $M(\Phi\pi\gamma)$ background subtracted distribution showing the number of F mesons found in each 30 MeV wide $M(\Phi\pi\gamma)$ slice. The curve is the result of a fit as explained in the text.

of possible reflections from other charmed mesons produced. In none of these studies do we find effects such as the one in figs. 2 and 4. We therefore interpret the observed peak as the F^* meson. Further supporting evidence is given by the decay angular distribution of the photon in the F^* rest frame with respect to the F^* direction which is consistent with being flat.

To determine the mass of the F^* , the $M(\Phi\pi\gamma)$ mass distribution was subdivided into slices. For each slice a fit was made to the $M(\Phi\pi)$ spectrum, using a third order polynomial plus a gaussian of fixed mass (1965 MeV) and fixed width (15 MeV). The number of F's was extracted from each fit and plotted as function of the $M(F\gamma)$ mass as shown in fig. 5. The distribution in fig. 5 was fitted by a gaussian plus a background with a shape as given by the Monte Carlo simulation. The resulting width is 29 ± 8 MeV in agreement with the 30 MeV width determined from the Monte Carlo simulation. We have repeated the fit with a fixed width of 30 MeV, yielding an uncorrected mass value of 2121 ± 9 MeV, and 45 ± 11 events in the peak.

The fitted mass value has to be corrected for the fact that, due to the limited photon energy resolution, the photon energy cut off suppresses the lower tail of the F^* peak and effectively shifts the peak upwards in mass. From the Monte Carlo simulation we obtain a correction of -12 MeV to $M(F^*)$ resulting in an F^* mass of $2109 \pm 9 \pm 7$ MeV. The last error is systematic and includes a 5 MeV error from the photon energy calibration, a 4 MeV error for the uncertainty in the mass correction and a 3 MeV error in the magnetic

field calibration, all added in quadrature. Using the F mass value of 1965 ± 3 MeV obtained from a fit to fig. 2b, this corresponds to a mass difference $\Delta M = M(F^*) - M(F)$ of $144 \pm 9 \pm 7$ MeV.

Correcting the observed number of events for the detection efficiency, 0.70 ± 0.10 , for photons coming from an F^* with momentum larger than 1.8 GeV/c, gives 64 ± 18 events. Together with the total observed number of F's corresponding to an F^* momentum cut off of 1.8 GeV, 58 ± 14 , we find that on the average more than 66% (84% CL) of the observed F mesons are produced from F^* mesons.

In summary we have observed a peak in the $F\gamma (F \rightarrow \Phi\pi)$ invariant mass distribution which we associate with the $J^P = 1^-, I = 0$ F^* meson. Its production and decay characteristics support such an interpretation. The mass of the F^* is determined to be $2109 \pm 9 \pm 7$ MeV corresponding to a mass difference $\Delta M = M(F^*) - M(F)$ of $144 \pm 9 \pm 7$ MeV.

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